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AGARDOGRAPH 286

Advanced Oxygen Systems for Aircraft
(Systèmes d'oxygène avancés)

Edited by

John ERNSTING
RAF School of Aviation Medicine

and

Richard L. MILLER
USAF Armstrong Laboratory

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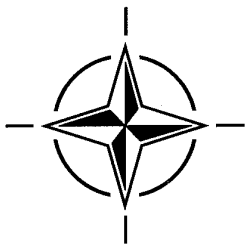

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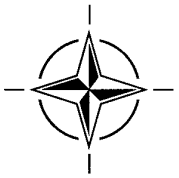

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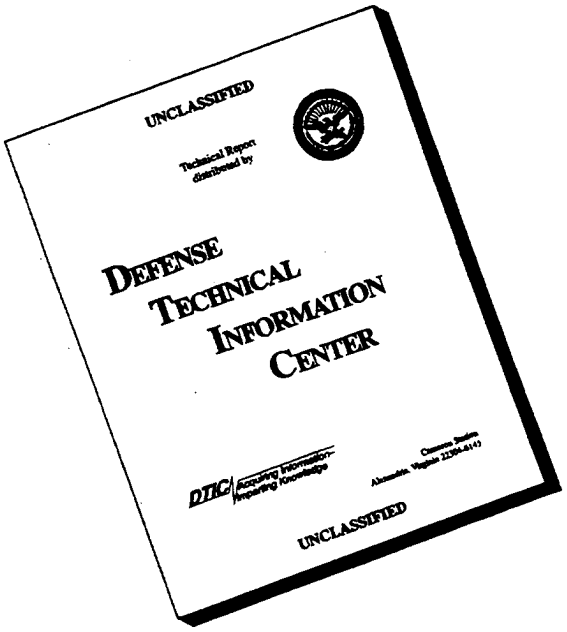

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- Improving the co-operation among member nations in aerospace research and development;
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Advanced Oxygen Systems for Aircraft

(AGARD AG-286)

Executive Summary

Many of the oxygen systems fitted to present NATO fighter aircraft employ liquid oxygen stores which have to be replenished. Some of these systems impose undesirable physiological loads on the aircrew and many do not provide all of the facilities which are required when operating in a high sustained $+G_z$ environment. The last 15 years has seen the development of practical on board oxygen generating systems (OBOGS) employing molecular sieve pressure swing adsorption technology. The first generation of OBOGS oxygen concentrators have now been in use in the US Navy (AV-8B), the US Air Force (F-15E and B-1B) and the Royal Air Force (Harrier GR5/7) for up to 10 years. Operational experience has amply confirmed the great advantages of OBOGS with the elimination of the large logistic train required for the production and delivery of liquid oxygen to the aircraft converter and the much greater reliability of OBOGS as compared with conventional liquid oxygen systems. The same period has also seen the full development of pressure breathing as a very effective technique for enhancing aircrew performance at high sustained $+G_z$ accelerations. Finally, increasing attention has been paid over the last two decades to the development of aircrew NBC respirators, to provide an ability to operate in a chemical and biological warfare environment.

This monograph is the first comprehensive published review of the design and performance of Advanced Oxygen Systems. It has been written principally by present and past members of the USAF Armstrong Laboratory and of the RAF School (formerly Institute) of Aviation Medicine who have been involved with defining the performance required of Advanced Oxygen Systems and with the design and assessment of the first and later generations of these systems.

The monograph provides indepth accounts of:- the physiological requirements for Advanced Oxygen Systems including composition of the breathing gas, resistance to breathing, and pressure breathing with G and at altitude; the deficiencies of current oxygen systems; pressure swing adsorption technology using molecular sieve which is the method of choice for the onboard generation of oxygen; all the molecular sieve oxygen generating systems developed and flown in the United States and the United Kingdom; and the design and performance of pressure demand regulators, connectors and aircrew masks for Advanced Oxygen Systems. It provides up to date discussions and recommendations on all aspects of the design of Advanced Oxygen Systems for future high performance combat aircraft. Finally, it provides a review of the effects of potential bleed air contaminants, including chemical warfare agents, on molecular sieve oxygen generating systems.

The monograph will be of value to all those concerned with the procurement, provision and operational use of Advanced Oxygen Systems fitted to the high performance combat aircraft now in development, including the F-22, Eurofighter 2000 and Rafale, and those to be designed in the future.

Systèmes d'oxygène avancés

(AGARD AG-286)

Synthèse

Bon nombre des systèmes d'oxygène équipant les avions de combat des forces aériennes de l'OTAN font appel aux bouteilles d'oxygène liquide qui doivent être renouvelées. Certains de ces systèmes imposent aux équipages des charges physiologiques indésirables et n'assurent pas l'ensemble des fonctions requises pour opérer sous facteur de charge élevé et soutenu +Gz. Les 15 dernières années ont vu le développement de systèmes de génération d'oxygène (OBOGS) pratiques aéroportés, basés sur les technologies du tamis moléculaire à adsorption modulée en pression. La première génération de concentrateurs d'oxygène OBOGS est en service avec l'US Navy (AV-8B), l'US Air Force (F 15-E et B-1B) et la Royal Air Force (Harrier GR5/7) depuis 10 ans environ. L'expérience opérationnelle a largement confirmé les avantages importants offerts par l'OBOGS et notamment l'élimination du train logistique considérable nécessaire pour la production de l'oxygène liquide et son acheminement vers le convertisseur embarqué, ainsi que la plus grande fiabilité de l'OBOGS comparé aux systèmes à oxygène liquide traditionnels. La même période a vu également le développement complet de la technique de respiration sous pression pour améliorer les performances des équipages en environnement de facteurs de charge élevés et soutenus +Gz. Enfin, au cours des deux dernières décennies, un intérêt grandissant a été porté au développement des masques à oxygène NBC qui permettent de fonctionner en environnement de guerre chimique et biologique.

Cette monographie est la première analyse complète de la conception et des performances des systèmes d'oxygène avancés à être publiée. La majeure partie des travaux de rédaction a été réalisée par des membres actuels et anciens de l'USAF Armstrong Laboratory et de la RAF School (anciennement le RAF Institute) of Aviation Medicine, qui ont participé à la définition des performances requises pour les systèmes d'oxygène avancés, ainsi qu'à l'étude et à l'évaluation de la première génération et des générations futures de ces systèmes.

Cette monographie traite de façon approfondie les sujets suivants: les spécifications physiologiques des systèmes d'oxygène avancés y compris la composition du mélange respiratoire, la résistance à la respiration, et la respiration sous pression sous facteur de G et en altitude; les carences des systèmes d'oxygène actuels; les technologies d'adsorption modulée en pression par tamis moléculaire, qui est la méthode privilégiée pour la production d'oxygène de bord; l'ensemble des systèmes de production d'oxygène avec tamis moléculaire développés et mis en service aux Etats-Unis et au Royaume-Uni; et enfin la conception et les performances des régulateurs à pression sur demande, des connecteurs et des masques à oxygène pour les systèmes d'oxygène avancés. Cette publication est composée d'un texte de discussions et de recommandations concernant tous les aspects de la conception des systèmes d'oxygène avancés pour les avions de combat à hautes performances futurs. Enfin, elle donne un aperçu sur les effets des contaminants potentiels de l'air de prélèvement, y compris les produits de guerre chimique, sur les systèmes de production d'oxygène avec tamis moléculaire.

Cette monographie intéressera tous ceux qui sont responsables de l'achat, de la fourniture et de l'exploitation opérationnelle des systèmes d'oxygène avancés équipant les avions de combat en cours de développement, y compris le F-22, l'Eurofighter 2000 et le Rafale, ainsi que les avions à venir.

Contents

Preface

This monograph had its origin 15 years ago when one of us was privileged to spend a sabbatical year at the USAF School of Aerospace Medicine with a mandate from the Royal Air Force to prepare proposals for the operational, physiological and design requirements for oxygen systems for future high performance combat aircraft. This activity occurred at a very appropriate time as the first practical method of generating breathing gas for aircrew on board an aircraft had very recently been man-rated by the School, which was becoming increasingly involved in the experimental study of molecular sieve oxygen concentrators systems. The desire of the USAF School of Aerospace Medicine (SAM) and the RAF Institute of Aviation Medicine (IAM) to improve the performance of oxygen systems to ensure that future systems would provide good protection at high altitude, at high $+G_z$ accelerations and in a chemical warfare environment led to intense collaboration between the two research organizations on all aspects of Advanced Oxygen Systems for aircrew operating high performance aircraft. Improved physiological requirements were developed and agreed (they were subsequently adopted internationally by the ASCC Nations and by NATO); design concepts for the first generation of advanced oxygen systems were discussed in depth by the two Institutions and problems arising during development were explored in a collaborative manner, each partner contributing its unique facilities and techniques to determine the best solution. The last ten years have seen the introduction into service in the US Navy, the US Air Force and the Royal Air Force of several aircraft (AV-8B, F-15E, B-1B and Harrier GR5/7) equipped with molecular sieve oxygen generation systems. Both USAF SAM (now the Armstrong Laboratory), and RAF IAM (now the RAF School of Aviation Medicine) have been closely involved in the development and assessment of these systems.

We felt that it would be appropriate as the new technologies relating to oxygen systems for military aircraft and particularly future high performance agile combat aircraft were being adopted more widely within NATO to record the experience in this field to date and to propose the performance which should be required of Advanced Oxygen Systems in order to provide the greatest possible enhancement of aircrew performance in combat. Accordingly we sought and obtained the agreement of the Aerospace Medical Panel of AGARD that we should prepare a monograph on Advanced Oxygen Systems for Aircraft for publication as an AGARDograph.

This monograph is a joint effort between past and present members of the Crew Technology Division of the Armstrong Laboratory and of the RAF School of Aviation Medicine. The editors wish to acknowledge the enduring enthusiasm of their fellow authors in the preparation of this monograph which had, for good reasons, a very long gestation.

As will be apparent to the reader, we decided at the beginning of the preparation of this monograph that each author should write his contribution in his native English. We make no apology for this approach. We also took a pragmatic approach to units of measurements, allowing authors to use the units which they employ in their work and adding, where necessary, the equivalent in SI units in parenthesis.

Many individuals in government establishments and industry have willingly supported this project for which we are most grateful. We should also like to thank Mr David Rabinowitz of Krug International, Inc., and Mrs Shirley Blackford and Squadron Leader Terry Adcock of the RAF School of Aviation Medicine for their help in the preparation of this final manuscript. Any errors must, however, be attributed to us.

We hope that all those interested in enhancing the well being, performance and safety of the aircrew who are to operate the high performance agile combat aircraft of the future will find this monograph of value in the design of Advanced Oxygen Systems for these aircraft.

John Ernsting
Richard L Miller

8 December 1995

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Chapter 1

INTRODUCTION TO THE MONOGRAPH

John Ernsting

INTRODUCTION

The last twenty years has seen the evolution and development into practical equipment of entirely new methods of providing breathing gas to the crews of military aircraft. The value of positive pressure breathing as a means of enhancing aircrew performance at high sustained $+G_z$ accelerations has been proven and accepted during the same period of time (8). There has also been an increasing emphasis on the provision of personal protection to enable aircrew to operate in a chemical warfare environment. The design and performance of the oxygen systems to be installed in the next generation of highly agile combat aircraft now under development in several NATO countries assumes increased importance. It is highly desirable that these Advanced Oxygen Systems utilise the new techniques for the generation of breathing gas on board the aircraft and provide enhanced performance and protection.

This monograph provides a coherent account of the requirements for, and design of, Advanced Oxygen Systems for military aircraft, with particular emphasis on the oxygen systems which should be fitted to the agile high performance fighter aircraft now under development for the air forces of the NATO nations. The principles of operation of systems for the on-board generation of breathing gas are considered, together with the physiological and operational requirements for these Advanced Oxygen Systems. The relevant features of the first generation of advanced oxygen systems employing molecular sieve technology to generate breathing gas in flight are described, and the lessons to be learnt from these systems are considered in depth.

HISTORICAL BACKGROUND

From the earliest days of aviation to the present time, the hypoxia induced by breathing air at altitudes above 10,000 feet has reduced the effectiveness of military aircrew in peace and war and taken its toll as a direct or indirect cause of fatalities (5). The importance of maintaining an adequate partial pressure of oxygen in the inspired gas on ascent to altitude had been recognised in the middle of the 19th century by Paul Bert (2). Gaseous and liquid oxygen were used widely by the combatants in World War I to prevent hypoxia at altitude, but the methods of delivering oxygen to the respiratory tract were generally crude and not very effective. Although considerable efforts were expended in the 1920s and 1930s in the development of full pressure suits for use in high altitude flight, oxygen delivery systems remained relatively primitive. The German Air Force had, however, by the outbreak of World War II in 1939, developed an efficient demand oxygen system (7). The United Kingdom proceeded to develop the economiser oxygen system (4) which, although it employed a continuous flow of oxygen and a reservoir, provided effective safety pressure which proved to be a very efficient and robust oxygen delivery system which continued in use, in certain Royal Air Force aircraft, for nearly 50 years. The early 1940s saw the development and introduction into service of demand systems in combat aircraft in the United States. By the end of the 1940s, pressure demand systems had been widely adopted as the means of delivering supplemental oxygen to the crews of fighter aircraft (4). In parallel, pressurisation of the cabin had become the primary means of protecting aircrew against the effects of exposure to low barometric pressure. It was decided, in view of the weight penalties and the increased risk of loss of crew and aircraft as the result of decompression, especially in combat, that the cabin pressure differential employed in fighter aircraft should be relatively low. The crew were therefore protected against hypoxia at altitude partly by pressurisation of the cabin and partly by the use of supplemental oxygen. This concept is as sound today as it was when it was evolved in the 1940s. Thus the cabins of virtually all present day high performance fighter aircraft are pressurised to a maximum pressure of 5 lbf in^{-2} (34.5 kPa) and the aircrew breathe gas from the oxygen system throughout flight. It is unlikely that this practical compromise will change in any future high performance agile combat aircraft.

The immediate decade following World War II saw the development of the basic elements of oxygen systems designed for use in fighter aircraft, which remain widely used today in the fighter aircraft of most NATO nations (4). Thus a replenishable store of oxygen is carried in the form of liquid oxygen, whilst high pressure gas storage is used for emergency supplies. The flow of gaseous oxygen from the liquid oxygen converter is controlled by a pressure demand regulator where the oxygen is usually diluted with cabin air. The resultant breathing gas mixture is carried to the aircrew mask which is fitted with inlet non-return and compensated outlet valves. Differences in the layout of these basic components which evolved in the 1950s and 1960s principally concerned the location of the pressure demand regulator and the connectors in the low pressure delivery system. The first generation of the post war oxygen systems had the demand regulator mounted in a side console of the cockpit and indeed this site is still widely employed in the fighter aircraft of the United States Air Force. The pressing need to provide ejected aircrew with an efficient underwater breathing facility in order to aid survival on descent into water led the United States Navy to locate the pressure demand regulator on the crew member, initially in the aircrew mask and later on the chest. Whilst the first generation of jet engine fighter aircraft developed for the Royal Air Force and Royal Navy employed panel mounted pressure demand regulators, the advantages of mounting the regulator on the ejection seat led to the adoption of this site in the early 1960s. Although the purchase by the United Kingdom of the United States Navy version of the Phantom aircraft in the mid 1960s led to the introduction of chest mounted regulators into the Royal Air Force and the Royal Navy, the pressure demand regulator

has been seat mounted in high performance fighter and fighter bomber aircraft built for the Royal Air Force since the early 1970s (4). Other European countries developing fighter aircraft, especially France and Sweden, have also mounted the pressure demand regulator on the ejection seat.

The NATO air forces have, therefore, a wealth of experience in fighter aircraft of the performance, operational suitability and reliability of oxygen systems comprising liquid oxygen storage, pressure demand regulators mounted on the side console, on the ejection seat and on the aircrew member, and a variety of aircrew masks. This experience, and the lessons which can be learnt from it, are considered in depth in the Chapter 2 of this monograph.

ONBOARD GENERATION OF BREATHING GAS

The considerable operational, safety and financial disadvantages of liquid oxygen as the source of breathing gas led to several attempts in the 1960s to develop systems whereby oxygen-rich breathing gas could be generated on board an aircraft. The breakthrough came with the adoption of pressure swing adsorption using synthetic molecular sieves. This development was stimulated by the decision of the United States Navy to phase out liquid oxygen manufacturing plants as soon as possible following two serious fires on board aircraft carriers. All first generation advanced oxygen systems now in service employ molecular sieve oxygen concentrators and Advanced Oxygen Systems now under development for the next generation of agile combat aircraft will use molecular sieve technology to generate breathing gas in flight. The historical development of various forms of on board generation of breathing gas are reviewed in Chapter 3 of this monograph. The principles of molecular sieve pressure swing adsorption technology are described in Chapter 6.

At first sight a potential disadvantage of the processing of engine bleed air to produce breathing gas is that the bleed air is sometimes contaminated with materials which may have an adverse effect upon the oxygen generation process, or are toxic to the aircrew member. Extensive studies, which are described in Chapter 11 of this monograph, have demonstrated that, provided some simple precautions are taken, molecular sieve oxygen concentrators are not affected adversely by bleed air contaminants and that they prevent toxic materials in the bleed air supply appearing in the product gas.

OPERATIONAL REQUIREMENTS

The replenishment of the liquid oxygen stores of fighter aircraft has always been an expensive and complex logistic procedure. An increasing requirement to operate these aircraft with minimal logistic support has intensified the interest of operational commanders in the on-board generation of breathing gas. The recent advent of aircraft capable of exposing aircrew to high sustained $+G_z$ accelerations at high altitude as well as low altitude, and the development of protective systems which employ the oxygen system to provide pressure breathing with G (8), have resulted in the formulation of new Operational Requirements for Advanced Oxygen Systems. Operational requirements for an Advanced Oxygen System are reviewed in Chapter 4 of this monograph.

PHYSIOLOGICAL REQUIREMENTS

The advent of the on-board generation of breathing gas and of new requirements such as pressure breathing with G, together with the unsatisfactory aspects of the performance of present oxygen systems, necessitated a searching review of the physiological requirements for the performance of these systems. The reviews conducted in the late 1970s and early 1980s, which resulted in the current ASCC and NATO standards for aircrew breathing systems (1,6), provide a firm basis on which to introduce additional feature such as pressure breathing with G and minimum coverage partial pressure assemblies for protection against hypoxia at high altitude. The physiological requirements for Advanced Oxygen Systems for future agile high performance combat aircraft are presented in Chapter 5 of this monograph.

CURRENT AND FUTURE ADVANCED OXYGEN SYSTEMS

The major design features of an Advanced Oxygen System are outlined in Chapter 4 of this monograph.

The last 15 years have seen the development and introduction into service of the first generation of oxygen systems employing molecular sieve oxygen concentrators (MSOC) to provide breathing gas. Thus the United States Navy, the United States Air Force and the Royal Air Force now have very considerable experience of operating aircraft in which the breathing gas for the crew is produced from engine bleed air using molecular sieve technology. The design and performance of the MSOC systems which have been developed and flown in the United States and the United Kingdom are described in Chapter 8.

The design and performance aspects of the major components of MSOC systems are considered, with emphasis on the areas where improvements are required, in several chapters. Chapter 7 reviews the breathing gas delivery system, particularly the demand regulator and the aircrew mask. The sensors, indicators and controls required in an Advanced Oxygen System are described and discussed in Chapter 9. Finally, the practical aspects of the design and performance of Advanced Oxygen Systems (lessons learnt and guidelines for future systems) are presented in detail in Chapter 10.

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Chapter 2

CONVENTIONAL AIRCRAFT OXYGEN SYSTEMS

John Ernsting

INTRODUCTION

The vast majority of high performance combat aircraft presently being operated by the NATO nations are fitted with conventional oxygen systems in which a replenishable store of oxygen is carried, most often as liquid oxygen, and the flow of gas to each crew member is controlled by an individual pressure demand regulator in which the oxygen is diluted with cabin air to provide breathing gas which is delivered through a hose and connectors to an oronasal mask which carries the appropriate valves. The design of many of these systems has changed only in detail over the last 40 years. Although these oxygen systems are highly reliable, they fail to meet the more recent physiological requirements. Many conventional systems place significant physiological loads on the aircrew and provide only marginal protection in certain emergency situations. Whilst some air forces have fitted a standard pressure demand system to successive generations of aircraft, others have introduced major changes of design with each new generation, aimed at improving the performance, simplifying the emergency drills and extending the protection provided by the system in the event of a malfunction of an essential component.

The general features and the performance of the major pressure demand oxygen systems fitted to high performance aircraft manufactured in the United States (US) and the United Kingdom (UK) are described in this chapter. Emphasis is placed upon the performance of each system both in normal operating and emergency situations. The first section of the chapter is devoted to the mode of storage of the main and emergency supplies of oxygen. Later sections consider the design and performance of the major types of pressure demand regulators and associated delivery systems, including the oronasal mask. The major features of present conventional oxygen systems are compared in the last section.

OXYGEN STORAGE SYSTEMS

The main oxygen supply in combat aircraft of World War II was carried as gaseous oxygen stored in steel cylinders charged to a maximum pressure of either 450 lbf $in^{-2}g$ [3,100 kPag] or 1,800 lbf $in^{-2}g$ [12,400 kPag]. The weight and size advantages of storing oxygen as liquid oxygen (11) led in the post-war period to liquid oxygen storage systems being fitted to virtually all high performance combat aircraft, as remains the situation today [except for those aircraft which are fitted with on-board oxygen generating systems]. The emergency/bail-out supply is stored as gaseous oxygen. High pressure gaseous storage systems continue, however, to be fitted to some training aircraft and to high differential pressure aircraft where oxygen is only used in the event of an emergency.

Gaseous Oxygen Storage Systems

Gaseous oxygen is stored at high pressure (1,800 - 2,200 lbf $in^{-2}g$ (12.400 - 15,160 kPag)) in stainless steel cylinders specially treated or wire wrapped in order to minimise shattering when hit by a projectile. The pressure of the oxygen is reduced by a reducing valve to the pressure required at the inlet to the pressure demand regulator. Precautions have to be taken to ensure that moisture is excluded from the storage system to avoid blockage of a pipe or valve by the formation of ice induced by low ambient temperatures and/or the low gas temperatures generated by expansion of gas when flow occurs in the system. Thus the water content of the oxygen used to charge the system must be very low [not to exceed 0.005 mg per litre at NTP conditions], charging hoses and connections must be purged with dry gas before use and the pressure in storage systems always be maintained above ambient pressure.

Gaseous oxygen storage systems have important advantages: they are relatively simple in construction, they are highly reliable, the supply is available immediately after charging, no gas is lost when the system is not in use and gauging of the contents of the system is simple and reliable. The very major disadvantage is that they are relatively heavy and bulky. Storage of oxygen at 1,800- 2,200 lbf $in^{-2}g$ [12,400 - 15,160 kPag] continues to be used for the back up, emergency and bail-out supply.

Liquid Oxygen Storage Systems

A typical liquid oxygen converter for a high performance aircraft comprises an insulated container, control valves, pipework and contents gauge (11,14). The liquid oxygen (typically 5 or 10 L) is held in a double-walled stainless steel spherical vessel. The space between the concentric walls of the vessel is fully evacuated and sealed to minimise heat transfer to the liquid oxygen. On the completion of the charging of the converter, the liquid oxygen in the pressure build-up coil vaporises and carries heat into the container. This process continues with warming of the surface of the liquid oxygen in the container until the operating pressure, typically 70 lbf $in^{-2}g$ (483 kPag), is reached. Heat continues, however, to leak slowly into the container so that the pressure within it continues to rise until, typically 10-12 hours after filling, it opens the relief valve. Thereafter gaseous oxygen is lost continuously from the converter so that 10% of the liquid oxygen in the container is lost in the 24 hour period after filling.

The liquid oxygen converter may either be secured to the airframe when it is charged in-situ, or easily removable when it can be either charged in a facility away from the aircraft or in-situ. Removing a discharged converter and replacing it with one which has been filled away from the aircraft can be accomplished in about 5 minutes.

The gaseous oxygen from the converter is warmed as it flows through the delivery pipework into the pressure cabin. A minimum length of pipework or a heat exchanger is provided in the pressure cabin to ensure that the temperature of the oxygen is raised to close to that in the cabin before it enters the demand regulator.

The transfer of liquid oxygen from the manufacturing plant to the liquid oxygen converter in the aircraft is a wasteful and expensive process both financially and in terms of man power. A large proportion of the liquid oxygen which enters the logistic train at the manufacturing plant is lost in the subsequent transfer and storage so that only about 10-15% of the liquid produced by the plant reaches the converter in an aircraft. The rate of loss of liquid oxygen from a converter (approximately 10% per 24 hour period) makes frequent recharging essential.

A serious potential disadvantage of liquid oxygen systems is the risk of contamination of the breathing gas by toxic materials including oxides of nitrogen, oxides of carbon and hydrocarbons. Such contamination may be derived from the atmospheric air used to manufacture the liquid oxygen or from the manufacturing plant, or the transport and handling equipment. These contaminants have higher boiling points than liquid oxygen and so they can accumulate in the container until a slug of contaminant passes with the liquid oxygen into the warming coil and evaporates to give a high concentration of contaminant in the gaseous oxygen delivered by the converter. Great care has to be taken to prevent the ingress of these contaminants and routine infra-red spectroscopy is performed with rigid standards for acceptable levels of contaminants (12).

Liquid oxygen storage systems have therefore considerable disadvantages. They are wasteful of oxygen and require complex ground dispensing equipment; time is required for the build up of pressure in the converter after charging, and extensive and strict precautions have to be taken to avoid contamination of liquid oxygen at all stages of manufacture and transfer to the aircraft converter. In addition, the complexity of a liquid oxygen converter results in a relatively high rate of failure of components. These disadvantages are, however, outweighed when the need to minimise the weight and size of the oxygen storage system is the most important consideration, as is the case in high performance combat aircraft (2). The proven, though very low, risk of fires and explosions arising in liquid and gaseous oxygen manufacturing plants and during the replenishment of aircraft stores and the need to separate re-arming and recharging of oxygen stores in time during rapid-turn-around of aircraft in war have contributed to the on-board generation of breathing gas becoming the method of choice for advanced high performance combat aircraft.

OXYGEN DELIVERY SYSTEMS

The layout of the major components of an oxygen delivery system in a high performance combat aircraft is determined principally by the site of the main pressure demand regulator which controls the flow of gas to the crew member. The principal sites which are employed in US and UK high performance combat aircraft are panel/console mounting, mounting on the ejection seat and mounting on the crew member either on the headgear (generally the mask) or the torso. The major features of each of these types of oxygen delivery system are considered in the following paragraphs.

United States Air Force Panel Mounted Regulator Systems

Oxygen systems installed in USAF fighter aircraft from the late 1940s to the present day (F-15, F-16 and A-10 aircraft) have employed a pressure demand regulator mounted on a side console of the cockpit (Figure 2.1).

There has been a progressive development of panel mounted pressure demand regulators from the type D-1 and D-2 of the 1950s through to the present type CRU-73/A regulator which is fitted to many current USAF combat aircraft. The slim line rectangular shape of the face of the CRU 73/A regulator minimises the panel space occupied by the regulator.

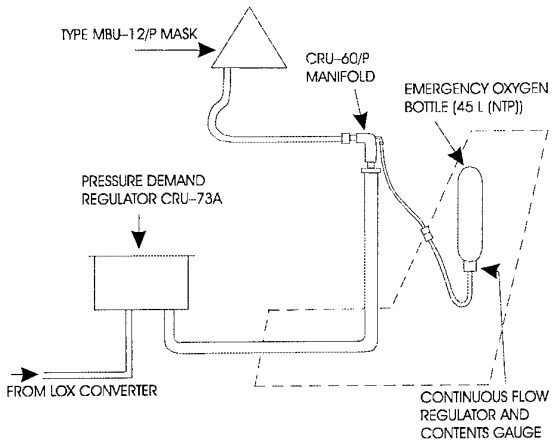

Fig. 2.1 A typical present day (1995) United States Air Force panel mounted oxygen regulator system for an ejection seat aircraft employing the chest mounted CRU-60/P oxygen manifold and a continuous flow emergency oxygen system.

The regulator provides 100% oxygen or oxygen diluted with cabin air on demand with safety pressure and pressure breathing for protection at altitudes up to 50,000 feet. It is designed to operate at oxygen supply pressures from 50 - 500 lbf $in^{-2}g$ [345-3,445 kPag]. The regulator delivers a safety pressure of +1 to +3 inch wg (0.25 - 0.75 kPag) at altitudes between 30,000 and 40,000 feet. Above 40,000 feet the delivery pressure increases linearly with fall of environmental pressure to 16 inch wg (4.0 kPag) at 50,000 feet. Breathing gas at a positive pressure of 4-6 inch wg (1.0 - 1.5 kPag) can be obtained at any altitude by selecting the emergency position of the Emergency Toggle. Holding this toggle in the mask test position provides gas at a pressure of 6 - 9 inch wg (1.5 - 2.25 kPag). A flow indicator (blinker) is operated by a diaphragm which senses the pressure drop created across the injector nozzle by the flow of oxygen. The regulator is also fitted with test points whereby the correct function of the control aneroids can be determined during ground test of the equipment.

The latest standard of panel mounted pressure demand regulator, the CRU-73/A, is normally set to deliver oxygen diluted with air which it provides on suction demand at cabin altitudes below 28,000 feet. The concentration of oxygen provided during typical cyclic breathing demand is of the order of 30-40% at ground level and increases to 38-45% at 15,000 feet (16). The suction required at the outlet of the regulator to induce a flow of breathing gas of 100 L(ATPD) min^{-1} at ground level with air dilution selected is only 0.8 inch wg (0.2 kPag)(15).

The breathing gas outlet of the pressure demand regulator is connected by flexible low pressure delivery hose to the CRU-

60/P oxygen manifold which is mounted on the torso harness on the front of the chest of the crew member (Figure 2.1). This connection is made by means of a pull-off connector which provides automatic separation of the low pressure oxygen delivery hose from the oxygen manifold on ejection and emergency ground egress. The wearer is warned of an inadvertent separation of the connector during flight by the imposition of an inspiratory resistance of the order of 4-6 inch wg (1.0 - 1.5 kPag). The inlet hose of the oxygen mask is secured to the locking bayonet outlet of the manifold whilst the hose from the emergency oxygen supply is secured to the manifold block by a bayonet connector. The inlet connection of the CRU-60/P oxygen manifold also contains an excess pressure relief valve whereby, when the main oxygen delivery hose is disconnected and the continuous flow emergency oxygen supply is activated, the flow from the latter can escape to ambient whenever the emergency oxygen flow exceeds the inspiratory flow demanded by the wearer.

The breathing gas provided by the demand regulator is delivered to the aircrew member by means of the pressure breathing oxygen mask type MBU-12/P. The mask, which presents a reflected edge seal to the face, comprises a silicone rubber facepiece moulded to a plastic hardshell. It is made in four sizes. The mask is secured on each side to the aircrew helmet by means of a pair of adjustable length straps and standard bayonet and receptacle connectors. The flow of gas into and out of the mask is through a combined inhalation-exhalation valve which is identical to that fitted to the earlier MBU-5/P mask. The passage for the flow of expired gas from the combined valve to ambient is, however, larger in the MBU-12/P mask. The mask also carries a microphone. The inhalation valve of the mask is connected by a 17 inch (42.5 cm) length of flexible corrugated silicone hose to the CRU-60/P oxygen manifold by means of a three-pin locking bayonet connector. A restraint cord to prevent overstretching of the flexible hose is fitted within its lumen. The resistance to breathing imposed by the combined inhalation and exhalation valve and its mounting in the mask is considerable. Typical values for the respiratory resistance imposed by the MBU-12/P mask are presented in Table 2.1.

Table 2.1 The resistance to respiration imposed at ground level by the USAF panel mounted regulator system comprising pressure demand regulator type CRU–73/A, low pressure delivery system including CRU–60/P manifold and MBU–12/P mask. Regulator set to deliver air dilution.

Peak Respiratory Flows (litre (ATPD) min^{-1})	Total change of Mask Cavity Pressure during the Respiratory Cycle (inch wg (kPa))	
MBU – 12/P Mask Alone		
50	2.0	(0.5)
100	3.5	(0.88)
150	7.0	(1.75)
200	12.2	(3.05)
Complete System		
50	2.5	(0.63)
100	6.1	(1.53)
150	11.5	(2.88)
200	20.0	(5.0)

The resistance to breathing imposed by this panel mounted regulator oxygen system with air dilution selected at ground level is also presented in Table 2.1. Whilst the resistance is within the present ASCC standard during quiet breathing, the system imposes resistances at peak respiratory flows greater than 70 L (ATPD) min^{-1} which are 65 - 70% greater than those specified in the current ASCC standard (1). The system, if the seal of the MBU-12/P mask to the face is adequate, also imposes additional transient increases in the resistance to expiration on extremes of head movement which produce extension of the mask hose. The increase in pressure which occurs in the mask hose when the extending force is removed is transmitted to the exhalation valve. The rise in pressure may be sufficient to interrupt speech. Expiratory difficulty may also arise during rapid ascent. Thus in this respect also the system fails to meet the physiological requirement that additional increases of mask pressure shall not exceed 1.0 inch wg (0.25 kPag) (1).

The USAF oxygen system includes an emergency oxygen (Figure 2.1) supply which can be selected manually in the event of a failure of the main supply in order to prevent hypoxia during the subsequent descent to a cabin altitude below 10,000 feet, and which is selected automatically on ejection to prevent hypoxia following ejection at high altitude. The emergency oxygen system comprises a small cylinder containing 45 L (NTPD) of oxygen compressed to 1,800 lbf $in^{-2}g$ (12,400 kPag) which is secured to the side of the ejection seat. A pressure gauge displays the contents of the bottle. Under many conditions of use, especially at medium and low altitudes, the setting of the inward and excess pressure relief valves of the CRU-60/P give rise to very large fluctuations of pressure in the mask cavity (of the order of 20 inch wg (5 kPag)) during the respiratory cycle, which can cause significant additional stress to the aircrew member (3,13). This system does, however, provide short duration protection against serious hypoxia at altitudes up to 50,000 feet.

Royal Air Force Panel Mounted Regulator Systems

Although the Royal Air Force ceased to operate fighter-bomber aircraft fitted with panel mounted oxygen regulators in 1993, it is of interest to record the form of the panel mounted regulator systems which were widely employed in high performance combat aircraft in the United Kingdom (UK) from the late 1950s (Figure 2.2). These panel mounted regulators were developed from the basic US type D1 regulator. A major change introduced into this regulator by the UK was a variety of pressure breathing schedules for the pressurisation of RAF partial pressure assemblies based upon the pressure jerkin (7). Another feature which distinguished the type D1 regulator and the UK series of panel mounted pressure demand regulators (Mk 17, 20 and 21) was the automatic provision of safety pressure at cabin altitudes above 10,000 - 12,000 feet which was a valuable method of preventing hypoxia due to an ill fitting mask.

The late 1950s saw the development and introduction into RAF aircraft of the personal equipment connector (Figure 2.2). This connector, the middle portion of which was secured to the side of the seat pan of the ejection seat, carried all the personal services from the airframe to the seat occupant including breathing gas, air for inflation of the G trousers, air to supply the air-ventilated suit and electrical connections to the microphone and telephones in the

headgear (11). The development of the personal equipment connector (PEC) was associated with several important advances in the design of oxygen systems for RAF aircraft (8). It allowed the introduction of locking connectors throughout the delivery system, thus eliminating the risk of inadvertent disconnection and hence removing the need for the inlet warning connector. The resistance to flow through

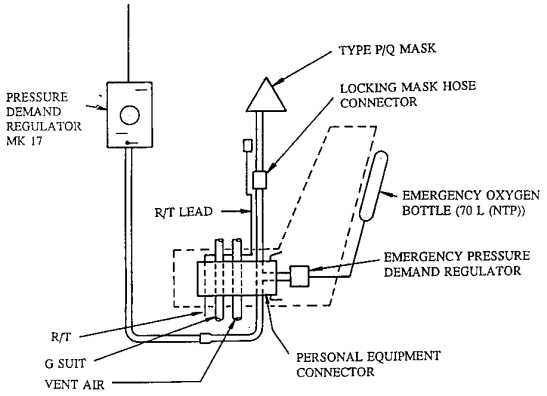

Fig. 2.2 A typical Royal Air Force panel mounted oxygen regulator system for an ejection seat aircraft (1958-1993) employing a personal equipment connector and pressure demand emergency oxygen set.

the oxygen port of the PEC was minimised. Considerable attention was also paid to reducing the resistance to flow through the whole of the low pressure delivery system by adopting smooth bore anti-kink hose where flexibility was required, together with light alloy tubing. The pressure drop from the outlet of the pressure demand regulator to the inlet hose of the mask was typically 0.8 inch wg (0.2 kPag) at a flow of 100 L (ATPD) min^{-1} (9). Finally, the PEC provided a means of permanently connecting the emergency oxygen supply into the low pressure delivery system (Figure 2.2). The early 1960s saw the introduction of a simple pressure demand regulator to control the flow of oxygen from the emergency oxygen bottle [capacity increased to 70 L (NTP)] to the crew member (8). Operational experience of the PEC in the Royal Air Force firmly established its value as the means of making and releasing - manually or automatically - all the services between the personal equipment and the supply systems.

Although initially the UK used the US type A13A mask in pressure demand oxygen systems, the bulk, poor sealing qualities and relative discomfort of this mask led rapidly to the development of the type P (large size) and type Q (small size) pressure demand masks which were introduced into the Royal Air Force in the late 1950s. The mask (Figure 2.3) comprises a flexible silicone facepiece with a reflected edge which seals on the front of the face immediately around the mouth and nose and does not include the chin. The facepiece is supported by a rigid exoskeleton which is suspended from the aircrew helmet by a flexible wire harness which incorporates turnbuckles by means of which a comfortable mask fit and good seal can be obtained. This suspension harness includes a toggle (Figure 2.3), rotation of which forces the mask firmly onto the face thereby providing an excellent seal at breathing pressures up to at least 70 mm Hg (9.3 kPag)(7, 10). The mask valves comprise a single low resistance inlet non-return valve with iceguard and a compensated expiratory valve. Some versions of the mask also carry an anti-suffocation valve which opens at a suction of 5 - 7 inch wg (1.25 - 1.75 kPag) in the event of cessation of the breathing gas supply. The resistance to breathing imposed by the present standard of type P/Q mask is presented in Table 2.3. The advent of a pressure demand mask with excellent sealing properties rapidly drew attention to the resistance to expiration and disturbances of speech produced by rises in mask pressure due to head movement ("mask hose pumping")(6). Reducing the degree of stretching of the mask hose by repositioning the mask hose connector and adding an internal restraint cord within the mask hose proved to be only partial palliatives for this annoying deficiency.

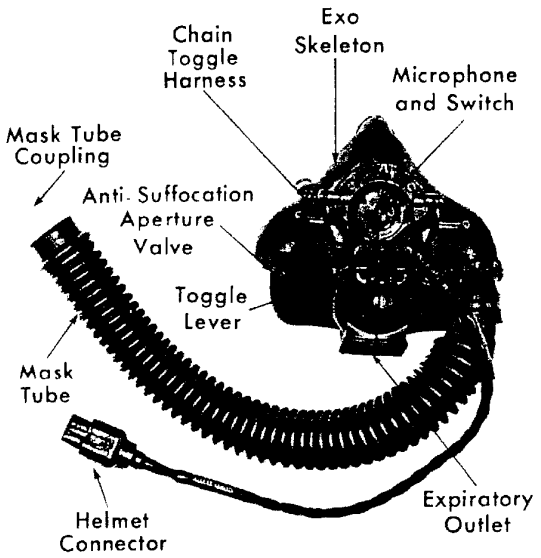

Fig. 2.3 The Royal Air Force pressure demand oxygen mask type P.

United States Navy Man Mounted Regulator Systems

Emphasis on the need to provide the naval aviator who has ejected over water with a supply of breathing gas during his subsequent immersion in order to increase his ability to survive in these circumstances led the US Navy to adopt a radically different approach to the location of the pressure demand regulator in their high performance combat aircraft (8). Sea survival considerations and the wish to improve the overall performance of the oxygen system, especially to reduce the resistance to breathing, led to the decision to mount the pressure demand regulator directly on the oronasal mask (type A13A mask). In parallel, following a series of serious in-flight incidents due to toxic fumes in the cockpit, it was decided that an air dilution facility was not required. An associated factor was the provision of a large [200 L(NTPD)] store of gaseous oxygen in the lid of the Rigid Seat Survival Pack which remained secured to the aircrew member following separation from the ejection seat during the ejection sequence, and the subsequent lowering of the liferaft and other survival aids. The oxygen supply from the liquid oxygen converter at a nominal pressure of 70 lbf $in^{-2}g$ [482 kPag] was carried through a composite disconnect mounted on the Rigid Seat Survival Pack and thence by a flexible narrow bore hose to the mask mounted regulator. The emergency oxygen supply in the Rigid Seat Survival Kit, which was fitted with a contents gauge and a manual control,

passed through a reducing valve into the oxygen port of the composite disconnect.

A variety of very small lightweight (65g) pressure demand regulators were developed for mask mounting in the 1960s (8). These regulators delivered 100% oxygen with a nominal fixed safety pressure of 2 inch wg (0.5 kPag) between ground level and 38,000 feet and provided pressure breathing above 40,000 feet to a pressure of 17 ± 3 inch wg (4.25±0.75 kPag) at 50,000 feet. The regulators employ either a simple tilt demand valve or pneumatic servo control of the demand valve. They have a high flow capacity and impose a low resistance to breathing. The arrangement of mask mounted regulator and associated emergency oxygen supply provide an excellent underwater breathing facility. These regulators are now almost exclusively torso mounted in the high performance combat aircraft of the United States Navy (4). The type MBU-14/P mask (a variant of the MBU-12/P mask) is used with the torso mounted oxygen regulators. The resistance to breathing imposed by this oxygen delivery equipment (Table 2.2) is relatively low and only just exceeds the limits specified in the ASCC standard (1). The introduction of a flexible hose between the regulator and the mask has, however, given rise to transient expiratory difficulties due to mask hose pumping (4).

Table 2.2 The resistance to respiration imposed at ground level by the USN chest mounted regulator system comprising type CRU–79/P pressure demand regulator and type MBU–14/P mask.

Peak Respiratory Flows (litre (ATPD) min^{-1})	Total change of Mask Cavity Pressure during the Respiratory Cycle (inch wg (kPa))	
MBU – 14/P Mask Alone		
50	2.00	(0.5)
100	3.5	(0.88)
150	7.0	(1.75)
Complete System		
50	2.6	(0.65)
100	4.8	(1.2)
150	8.4	(2.1)

United Kingdom Man Mounted Regulator Systems

Development of a new generation of miniaturised air dilution pressure demand regulators was commenced by the United Kingdom in the mid-1960s (8). The decision to purchase the Phantom F-4 aircraft led to the adoption of torso mounted air dilution pressure demand regulators for a number of UK high performance aircraft, including the F-4 Phantom, the Jaguar and the Harrier GR1/3 and T4. A slim line personal equipment connector was developed to carry all the personal services, including medium pressure oxygen from the liquid oxygen converter and from the seat mounted emergency oxygen bottle to the aircrew equipment (8). This generation of UK regulators employed pneumatic control of safety pressure and pressure breathing so that it was possible to provide direct pneumatic control of the compensation of the expiratory valve through a second tube within the hose to the mask. These regulators provided air dilution, suction demand below 15,000 feet, a safety pressure of 1 - 2 inch wg (0.25 - 0.5 kPag) above 15,000 feet, and pressure breathing above 40,000 feet with a mean mask pressure of 16 - 18 inch wg (4.0 - 4.5 kPag) at 50,000 feet. The control of the compensation of the expiratory valve of the mask by the regulator gave a low resistance to breathing and eliminated the unwanted added resistance to expiration associated with mask hose pumping, rapid ascent and rapid decompression. The regulators also incorporated a second pathway (a continuous flow bypass or a demand regulator) by which oxygen was delivered to the mask in the event of a failure of the main regulator.

Whilst the performance of the UK man mounted oxygen regulator systems fully met the requirements of the ASCC standard (1), the provision of a complex regulator for each crew member was expensive, the regulators were liable to damage due to rough handling outside the aircraft, and the drills which had to be employed to exploit fully all the facilities which were provided by the system were complex. It was decided, therefore, in the late 1970s, not to employ man mounted oxygen regulators in future Royal Air Force high performance aircraft. These regulators are still in use in RAF Jaguar aircraft.

Royal Air Force Seat Mounted Oxygen Regulator Systems

Seat mounting of the pressure demand regulator has been employed in high performance and flying training aircraft developed for the Royal Air Force since the late 1970s [Tornado GR MK1/3 and F2/3, Hawk T MK1 and Tucano T MK1 aircraft]. The oxygen regulator package is attached to the seat portion of a personal equipment connector through which the oxygen supply (regulated to 80 lbf $in^{-2}g$ (550 kPag)) from the liquid oxygen converter and the seat mounted emergency oxygen supply (regulated to 45 lbf $in^{-2}g$ (310 kPag)) are fed to the regulator package, and breathing gas from the package is delivered through a mask hose assembly to the aircrew mask (Figure 2.4).

The regulator package consists of two pressure demand regulators, main and standby (8,11). Each regulator has a pilot valve which controls the flow of oxygen through a main demand valve and a breathing diaphragm which is gas loaded to provide safety pressure and pressure breathing. In order that the performance of the regulators could be optimised for either air dilution or 100% oxygen modes, the main regulator only provides air dilution (below 33,000 feet), whilst the standby regulator provides 100% oxygen at all altitudes. The main regulator provides safety pressure automatically at altitudes above 15,000 feet whilst safety pressure is provided at all altitudes by the standby regulator. Both regulators provide pressure breathing, the pressure increasing from 2 - 4 inch wg (0.5 - 1.0 kPag) at 40,000 feet to 16 - 18 inch wg (4 - 4.5 kPag) at 50,000 feet. A ground level pressure breathing facility (press-to-test) is provided on the main regulator only. A compensated dump valve is fitted at the common outlet of the two regulators. It is compensated to the pressure in the chamber on the control side of whichever regulator (main or standby) is in operation. Thus the dump valve opens and allows gas to escape from the regulator-mask hose whenever the pressure in the latter exceeds the control pressure acting on the breathing diaphragm of the regulator. The rise of mask cavity pressure on head movement, rapid ascent and a small leak of oxygen through the main demand valve is limited by the regulator dump valve to 1.0 inch wg (0.25

kPag). The dump valve also prevents the mask cavity pressure exceeding 22 inch wg (5.5 kPag) on rapid decompression or a full flow failure of the demand valve of the regulator.

The breathing gas supplied by the regulator package through the personal equipment connector is delivered by a type P or Q mask, fitted with an anti-suffocation valve (Figure 2.4).

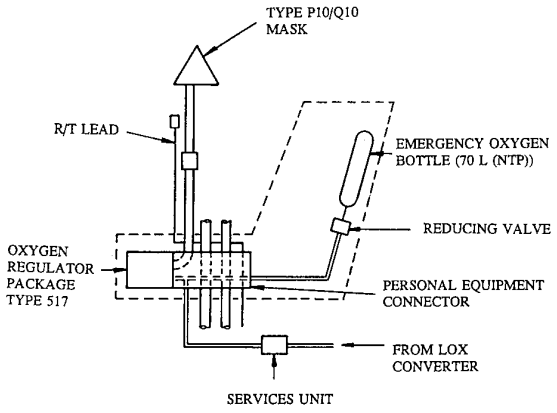

Fig. 2.4 The seat mounted oxygen regulator system of the RAF Tornado aircraft employing the type 517 oxygen regulator package and a personal equipment connector. The Services Unit includes a combined on/off and reducing valve, an oxygen flow sensor and a low pressure warning switch.

The oxygen port of the man portion of the personal equipment connector contains a self sealing valve which closes automatically when the man portion is disconnected from the seat portion. This valve prevents water entering the mask hose assembly on entry into water after ejection. Air is drawn into the mask through the anti-suffocation valve whenever the man portion of the connector is separated from the seat portion.

Table 2.3 The resistance to respiration imposed at ground level by the RAF Tornado Seat Mounted Regulator System comprising pressure demand regulator type 517, personal equipment connector, hose assembly and type P10 mask. Regulator package set to deliver air dilution.

Peak Respiratory Flows (litre (ATPD) min^{-1})	Total change of Mask Cavity Pressure during the Respiratory Cycle (inch wg (kPa))	
P10 Mask alone		
30	1.6	(0.4)
110	2.4	(0.6)
150	3.8	(0.95)
200	5.7	(1.43)
Complete System		
30	1.8	(0.45)
110	3.5	(0.88)
150	6.5	(1.63)
200	10.5	(2.63)

The resistance to breathing imposed by the seat mounted regulator system (Table 2.3) is within the limits specified in the ASCC standard (1), both in routine use with either air dilution or 100% oxygen selected, and on rapid ascent, rapid decompression and with mask hose pumping.

Operation of the seat mounted emergency oxygen control not only opens the emergency oxygen supply, it also selects the standby regulator. Thus operation of the emergency oxygen control automatically provides the seat occupant with an alternative oxygen supply (emergency oxygen) and an alternative regulator (standby regulator) - so that by this simple operation all major oxygen system failures (a failure of the main oxygen supply or the main regulator) are overcome and the flow of oxygen to the mask restored. This arrangement provides very simple emergency drills. The pressure at which emergency oxygen is supplied is significantly lower than the minimum pressure at which main oxygen is normally supplied. Thus, should the main supply be intact when the emergency oxygen control is activated, no emergency oxygen will be used. The aircrew member is able to decide whether or not the emergency oxygen supply is being used by reference to the emergency oxygen contents gauge which is mounted on the ejection seat at a site where it can be seen in flight.

This form of seat mounted oxygen regulator system has most of the features which are desirable in the oxygen system for a high performance combat aircraft. It probably represents the optimum compromise between the conflicting operational, physiological and engineering requirements.

COMPARISON OF THE FEATURES OF CONVENTIONAL AIRCRAFT OXYGEN SYSTEMS

The conventional demand oxygen systems fitted to the present high performance combat aircraft manufactured in the United States and the United Kingdom represent the culmination of many years of development and operational use. In considering the features which should be incorporated in advanced oxygen systems for future high performance combat aircraft, it is valuable to review the relative merits and disadvantages of these fully developed conventional pressure demand oxygen systems. Virtually all present conventional oxygen systems in high performance combat aircraft comprise a store of liquid oxygen, a pressure demand regulator, a low pressure delivery system, an oronasal mask and an emergency/bail-out gaseous oxygen supply. The major differences in design and performance are related to the location of the pressure demand regulator, whether it be panel mounted on a console in the cockpit, on the torso of the crew member or on the ejection seat. The relative merits of these three types of conventional pressure demand oxygen system which have been described in the preceding sections are considered and summarised in this section.

Main Oxygen Store

The main supply of oxygen in virtually all high performance aircraft is carried as liquid oxygen. This form of storage system has the lowest weight and occupies the smallest space of the available replenishable systems. Present liquid oxygen systems can provide gaseous oxygen at the required flows, pressures and temperatures, provided that the liquid oxygen within the converter is fully stabilised and that the size of the heat exchanger in the gaseous oxygen delivery line is

adequate. The major disadvantages of liquid oxygen are the complexity and cost of the manufacturing and supply system, the risk of contamination with toxic materials, the time taken for the delivery pressure to build up after filling, and the relatively high rate of mechanical defects of converters. These disadvantages have, however, been accepted for fighter aircraft for over 40 years in order to minimise the weight and bulk of the oxygen storage system. Other disadvantages, which relate to any replenishable oxygen storage system, are the risks of fire and explosion in the manufacturing plant and oxygen transport system, and the prolongation of the time taken to turn around an aircraft by the need to cease other operations such as re-arming whilst the oxygen store is replenished. These disadvantages of replenishable stores of oxygen in aircraft and the disadvantages of liquid oxygen storage can be overcome by generating the breathing gas from air on board the aircraft (Chapters 3 and 4 refer).

Panel Mounted Regulator Systems

The arrangement of the components of the panel mounted oxygen regulator system fitted to USAF high performance aircraft is such that on cockpit entry, the aircrew member has to connect the main and emergency supply hoses to the CRU-60/P oxygen manifold mounted on his torso harness. The use of a personal equipment connector in such a system allows these connections and other personal services to be made in a single operation. Panel mounted pressure demand regulators are highly reliable items with a performance which of itself could meet the present standard of physiological requirements (1, Chapter 5). The resistance to flow presented by the low pressure delivery pipes and connectors and the valves of the MBU-12/P mask result in resistance to breathing (Table 2.1) being considerably greater than that allowed by the ASCC standard (1). Mask hose pumping, rapid ascent and rapid decompression produce excessive increases of pressure in the mask. The concentration of oxygen delivered by the system at altitude when air dilution is selected meets the physiological requirements with regard to the prevention of hypoxia during routine flight and following decompression to high altitude, and the avoidance of acceleration atelectasis and delayed otitic barotrauma. The absence of safety pressure in the mask at cabin altitudes between 15,000 and 28,000 feet may, however, result in hypoxia in the presence of an ill-fitting mask particularly at the higher altitudes. Manual selection of safety pressure at altitudes below 28,000 feet will provide good protection against in-board leakage although the level of mask pressure will exceed the limits of the ASCC specification (1) and may give rise to respiratory discomfort and fatigue if employed for any length of time.

Failure of the main oxygen supply or of the panel mounted regulator to deliver oxygen may be signalled by the operation of a warning of low LOX contents or low gaseous oxygen pressure, by the absence of cyclic operation of the blinker of the regulator or by the symptoms of hypoxia. The corrective drill is simple and comprises selection of emergency oxygen, disconnection of the oxygen delivery hose from the CRU-60/P oxygen manifold (to allow operation of the inward and excessive pressure relief valves), followed by immediate descent to below a cabin altitude of 10,000 feet. The emergency oxygen system imposes a very high resistance to breathing which is very uncomfortable and distracting (3,13). These effects can be obviated by the aircrew member disconnecting the mask hose from the CRU-60/P oxygen manifold once he is below 10,000 feet. There is no means available for the main oxygen supply to be used in the event of a failure of the main pressure demand regulator to deliver breathing gas.

Torso Mounted Regulator Systems

Mounting a miniaturised pressure demand oxygen regulator on the torso can provides a system which imposes a low resistance to breathing during routine flight, as is the case with both US Navy and RAF chest mounted regulator systems. Mask hose pumping, rapid ascent and rapid decompression can, however, give rise to high mask pressures unless the compensation of the expiratory valve of the mask is provided directly from the control chamber of the regulator which involves a second pneumatic connection between the regulator and the mask, as is provided in RAF chest mounted regulator systems. The provision of this facility does, however, increase considerably the cost of the mask and regulator. The acceptance of the physiological and operational disadvantages of the use of 100% oxygen throughout flight results in a small, lower weight and less complex pressure demand regulator than if air dilution is required as well as 100% oxygen. Nevertheless, the weight and size of the air dilution/100% oxygen chest mounted regulators used in the Royal Air Force are well within acceptable limits, especially as the regulator is mounted on the rigid closure plate of the life preserver. The injector mechanism of the air dilution facility does, however, produce noise and a noise attenuating mask hose is required to reduce the noise levels in the mask. The automatic provision of safety pressure above 15,000 feet when air dilution is selected, and at all altitudes when 100% oxygen is selected, provides good protection against hypoxia and inhalation of toxic fumes due to an ill-fitting mask.

A failure of the oxygen regulator to pass oxygen in the US Navy regulator system can only be overcome by disconnecting the mask hose so that cabin air can be breathed, and immediate descent to low altitude. Indeed, the emergency oxygen supply in the Rigid Seat Survival Kit can only be used if the remainder of the supply system, including the regulator and mask, are operating correctly. The emergency supply is essentially provided for the emergency of a failure of the LOX converter, ejection at high altitude and, more importantly, underwater breathing on immersion in water. The provision of an alternative regulator in the Royal Air Force chest mounted regulators does allow a sorties to be completed after a failure of the main regulator. The drills required to exploit this facility to the full are, however, rather complex, requiring a detailed analysis to determine which component has failed when the aircrew member becomes hypoxic. Realistic ground simulations are highly desirable in order to train aircrew in the recognition of various malfunctions and the appropriate corrective drills.

Seat Mounted Regulator Systems

Mounting the pressure demand regulator on the seat pan of the ejection seat provides a system which imposes a low resistance to breathing. Optimisation of the design of the regulator for either the air dilution or 100% oxygen mode, as in the RAF Tornado regulator package, provides a further reduction in breathing resistance. The automatic provision of safety pressure at cabin altitudes above 15,000 feet when the air dilution regulator is in use is close to the ideal in this

regard. The provision of safety pressure at altitudes from ground level to 40,000 feet when 100% oxygen is selected is also an ideal facility. The resistance to breathing imposed by the complete system is within the limits of the ASCC standard (1). The compensated dump valve at the outlet of the regulator package ensures that with standard mask valves, the rise of mask pressure caused by mask hose pumping, rapid ascent, rapid decompression and a high flow failure of the demand valve are also within the limits of the ASCC specification (1).

Duplication of the demand regulators and the inter-linking of the emergency oxygen control with the regulator selector, provides simple yet very effective aircrew drills in the event of a malfunction of a regulator or a source of supply of oxygen. This arrangement probably represents the ideal with respect to duplication of essential components with flexibility and the ability to complete a mission after a failure of the main demand regulator.

The features incorporated in the seat mounted regulator system for Tornado, both with regard to performance during routine flight and the provision of alternative facilities with simple user drills should be considered for inclusion in an advanced oxygen system for a high performance combat aircraft.

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Chapter 3

HISTORY OF ONBOARD GENERATION OF OXYGEN

Richard L. Miller and John Ernsting

INTRODUCTION

The concept of onboard generation of aviator's breathing oxygen originated in the early 1960's as an outgrowth of space program involvement with closed cycle life support systems oriented toward long term manned space flights. Much of the technology was concerned with the reclamation of potable water from waste liquids, and regeneration of oxygen from carbon dioxide (1,8). There is a natural extension of these developments from closed cycle application in spacecraft to semi-closed loop, and ultimately, to open loop application in aircraft. The technologies for oxygen generation in flight discussed in this chapter can be divided into those employing a supply of compressed air (air dependent systems), and those which do not require a supply of air (air independent systems).

AIR DEPENDENT SYSTEMS

Electrochemical Oxygen Concentration

The electrochemical oxygen concentration process operates on an ion exchange principle (5). Direct electrical current is used to electrochemically "pump" oxygen from an air stream through a sulfonated solid polymer electrolyte. The electrochemical cell is shown schematically in Figure 3.1. At the cathode, molecular oxygen is catalytically combined

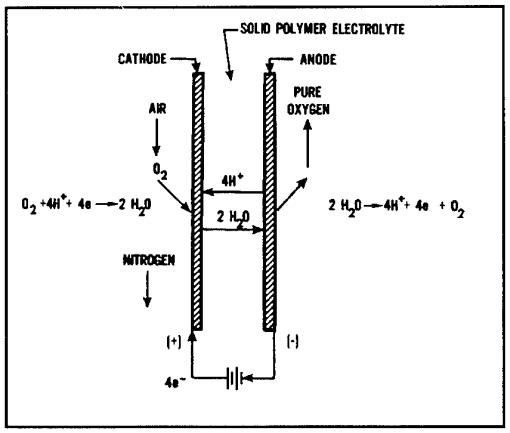

Fig. 3.1 Schematic of electrochemical oxygen concentrator cell.

with hydrogen ions contained within the electrolyte to form water.

The water molecules migrate through the electrolyte to the anode where they are electrolyzed, the oxygen evolving as a pure gas and the hydrogen returning to the electrolyte in ionic form. Although there is no net consumption of water in the system, the efficiency of the solid polymer electrolyte cell is greatest when both the air and oxygen sides of the membrane are saturated with water.

A typical electrochemical cell stack consists of 120 ten-inch diameter cells. The center plate of the stack contains inlet ports for both water and air, and outlet ports for oxygen and waste nitrogen. The cells are connected electrically in series and pneumatically in parallel. Engine bleed air is heated and passed through the stack at approximately 90 °C. The concentrator is capable of generating essentially 100% oxygen at a typical operating pressure of 400 lbf in^{-2} g (2,760 kPag). Hence, an oxygen compressor is not required. Water is recovered from the oxygen by cooling the gas in a heat exchanger fed by the aircraft environmental control system. The oxygen then passes into an accumulator. The rate of production of oxygen is controlled by regulating the electrical power to the cell stack.

A two-man prototype electrochemical oxygen concentrator was developed by General Electric Company for the U. S. Navy in 1974. Because of significant cell sealing problems which developed during laboratory environmental tests, the system was not flight qualified. Further development, test and evaluation of this form of onboard generation system was discontinued in the late 1970's.

Praseodymium-Cerium Oxide System

An air separation process using praseodymium-cerium (Pr-Ce) oxides was investigated in the mid-1970's by the Linde Division of Union Carbide (16) under a contract jointly sponsored by the Naval Air Development Center, and the Air Force Flight Dynamics Laboratory (now part of the Air Force Wright Laboratory). The concept was designed to provide high purity breathing oxygen based on reversible oxidation and dissociation of a praseodymium-cerium oxide mass in response to a temperature-pressure swing cycle (Figure 3.2).

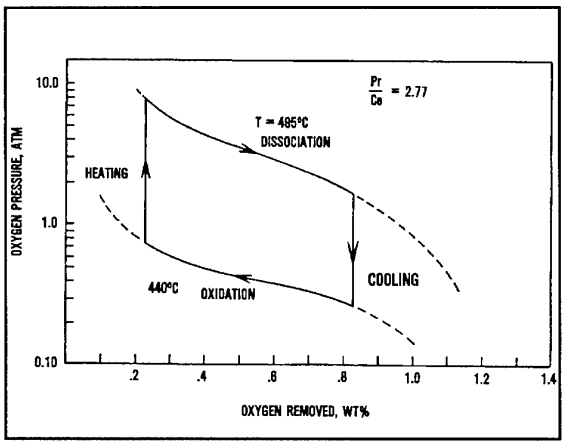

Fig. 3.2 Pressure-Temperature swing diagram for Praseodymium-Cerium Oxide oxygen generating system.

A laboratory reactor system was constructed which employed a Pr-Ce oxide containing 2.7 parts praseodymium to 1 part cerium (by weight) with 10% alumina binder, extruded in the form of pellets approximately 1.6 mm in diameter by 4.8 mm long. The temperature-pressure swing process cycle was set at three minutes, one minute each for oxidation and dissociation and 0.5 minute each for sensible cooling and heating. Oxidation was conducted at 440 °C and 10 ATA (1,013 kPaa) while dissociation occurred at 495 °C and 1 ATA (101 kPaa). Development of a working laboratory system involved a number of engineering difficulties, most of which were related to the problem of cycling the reactor temperature rapidly and uniformly to effect oxidation and dissociation. Based on this study, it was estimated that a two bed Pr-Ce reactor system to produce 26 L (NTP) min^{-1} of 90 to 98% purity oxygen would require 15.9 kg (35 lb) of Pr-Ce oxide, have a maximum power draw of 7 kilowatts, and would use approximately 2600 L (NTP) min^{-1} of process air, 740 L min^{-1} for oxidation and 1860 L min^{-1} for cooling. In view of its high power demand and air flow requirement, the Praseodymium-Cerium oxygen generation system was not developed beyond the laboratory stage.

Barium Oxide System (Brin Process)

Barium oxide when heated to 540 °C will react with molecular oxygen to form barium dioxide (peroxide). When the temperature of the barium dioxide is raised to 900 °C, the compound breaks down giving off molecular oxygen:

$$2\,BaO + 0_2 \underset{900\ °C}{\overset{540\ °C}{\rightleftharpoons}} 2BaO_2$$

The industrial application of this reaction, known as Brin's process, was used for the commercial production of oxygen until the air liquefaction process was perfected in the 1930's. In the mid-1960's, Bendix (now Litton Instruments and Life Support Division) adapted the Brin process for onboard generation of oxygen and developed a laboratory breadboard model system under a 1971 contract with the U. S. Navy (6). The basic process (Figure 3.3) used barium oxide pellets held in twin internally heated and insulated containers to maintain constant temperature in the range from 675 to 735 °C. During the charge portion of the oxygen generation cycle, oxygen was absorbed from process air at a pressure of 80 to 95 lbf in^{-2} absolute (552-655 kPaa). During the desorption cycle, oxygen was extracted from each bed, in turn, by a compressor which reduced the pressure in the bed to 2.0 lbf in^{-2} absolute (14 kPaa), and then raised the pressure of the oxygen to 1800 lbf $in^{-2}g$ (12,400 kPag) for accumulator storage and distribution to the crew. In order to maintain the efficiency of the barium oxide/peroxide, it was necessary to free the air feed of carbon dioxide, water vapor and oil by passing the incoming process air through activated charcoal, lithium oxide and molecular sieve filter elements.

A complete, two-man self-contained oxygen generator for on-aircraft production of 26 L (NTPD) min^{-1} of 99.5% purity oxygen had an estimated weight of 40 kg, an electrical power requirement of 3.3 kilowatts, and a process (engine bleed) air requirement of 284 L (NTP) min^{-1}. The complexity of the barium oxide system, its high power consumption and the "acceptance", in principle, of less than 100% oxygen concentration for aircraft breathing gas systems led to abandonment of the barium oxide approach in the mid-1970's.

Fluomine System

Fluomine, [bis(3-fluorosalicylaldehyde)ethylenediimine cobalt-II] is a solid organic chelate that forms a reversible coordination complex with molecular oxygen (Figure 3.4) at temperatures below about 50 °C. When the temperature of the fluomine-oxygen complex is increased to about 100 °C the reverse reaction is favored and molecular oxygen is released. For continuous generation of oxygen, a fluomine system thus consists of dual cyclic heat exchange beds, one

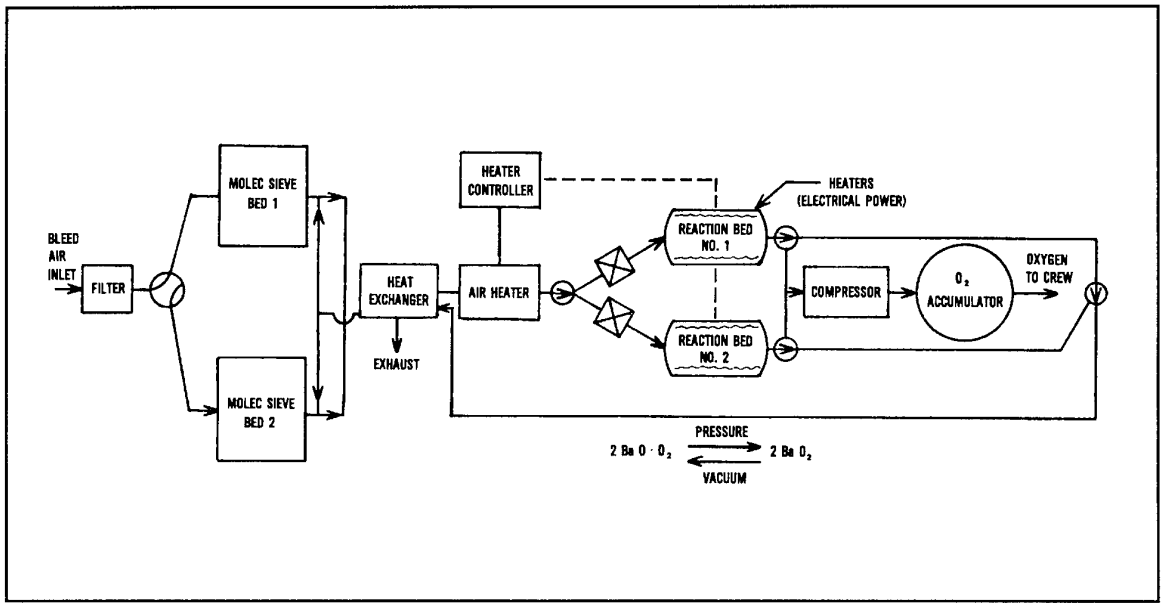

Fig. 3.3 Flow schematic of barium oxide (Brin Process) oxygen generating system.

bed sorbing oxygen from air while the other bed desorbs oxygen-rich product gas. The half-cycle length is approximately four minutes for a system with temperature swings between 25 and 100 °C. During the oxygen loading half-cycle, fluomine absorbs molecular oxygen from engine bleed air at a minimum pressure of about 25 lbf in^{-2} absolute (172 kPaa), while the nitrogen-rich exhaust is vented overboard the aircraft. During the desorption half cycle, fluomine is isolated from process air and heated to about 100 °C. Product oxygen is then pumped out of the bed by a multi-stage compressor which reduces the pressure in the fluomine bed to 7 lbf in^{-2} absolute (48 kPaa). The initial volume of air from the bed is discarded, and then the oxygen, liberated from the fluomine by application of heat and vacuum, is drawn into the compressor which raises the pressure of the oxygen to 1750 lbf in^{-2} g (12,100 kPag) for storage in the accumulator and distribution to the crew stations.

In the decade from 1970 to 1980, two different fluomine oxygen generation systems were developed, both by AiResearch Manufacturing Company of California (15). In 1972, a "two-man" system capable of generating 26 L

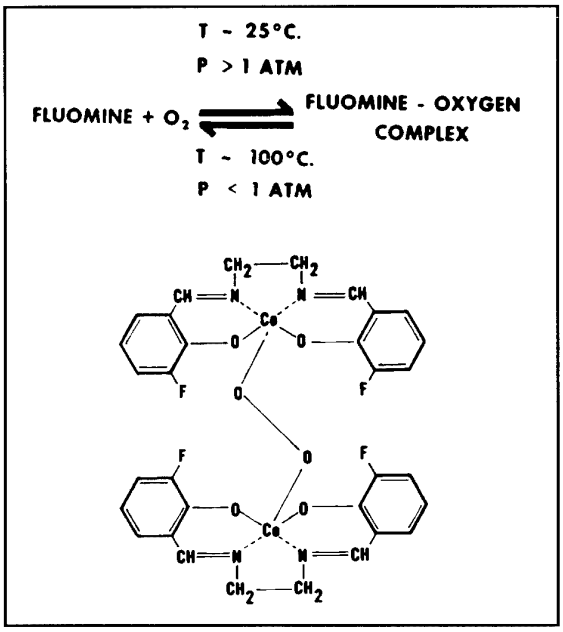

Fig. 3.4 Chemical structure of oxygenated fluomine.

(NTPD) min^{-1} of oxygen having a minimum purity of 98.5% oxygen was developed under contract to the U. S. Navy (13). This system was man-rated by the USAF (10), and flight tested in an EA-6B aircraft at the Naval Air Test Center. The performance of the system was considered marginal by the Navy, and further development of metal chelate absorption technology was subsequently abandoned in favor of pressure swing adsorption for onboard generation of oxygen in tactical aircraft. A second-generation fluomine oxygen system was developed by AiResearch under contract with the Air Force for application on the B-1A bomber program. This system, referred to as the Open Loop Oxygen Generating System (OLOGS), was a "four-man" unit, designed to produce 19.8 L (NTP) min^{-1} of oxygen with a minimum purity of 98.5 percent. The difference in oxygen production rate per crewmember is a reflection of the US Navy requirement for 100 % oxygen at all altitudes versus the Air Force use of "air-mix" or diluter-demand breathing gas regulation up to a cabin altitude of between 28,000 and 32,000 feet. The open loop oxygen generation system developed for the B-1A aircraft weighed 68 kg and required approximately 7.5 kilowatts of electrical power (230 VAC/400 Hz). Heat for oxygen desorption was supplied by electrically heated coolanol, pumped through channels in the fluomine bed. The bleed air requirement was about 312 L (NTP) min^{-1} at a maximum temperature of 66 °C, supplied at a pressure of from 50 to 75 lbf in^{-2} gauge (345-517 kPag).

The OLOGS was installed on B-1A Aircraft No. 4 in late 1978. During the period from January, 1979 to completion of the test program in April, 1981, the OLOGS accumulated over 143 hours of aircraft operating time including production test, ground checkout, and flight evaluation.

The Open Loop Oxygen Generating System had the advantage of producing a breathing gas containing over 98% oxygen, and, with a built-in compressor, it had the capability for in-flight refill of the breathing gas reservoir, which served as an emergency or backup oxygen supply in the event of failure of the concentrator or loss of engine bleed air. The disadvantage of the OLOGS was the high cost of the fluomine chemical itself, its relatively short lifetime (estimated at 300 operating hours), and its tendency to produce minor amounts of noxious chemicals, namely carbon oxides, as a result of chemical degradation (14). In fact, the product oxygen from the OLOGS routinely contained carbon dioxide in concentrations ranging from 300 to 1000 parts per million by volume (ppmv) and carbon monoxide in concentrations ranging from 3 to 15 ppmv. The contaminant concentration and hence rate of degradation of the fluomine chemical appeared to be related to the relative humidity and temperature of the process air. The development of fluomine-based onboard oxygen generating systems ceased with the cancellation of the B-1A program in 1978. When the B-1B bomber production program was reinitiated in 1981, the onboard oxygen system was converted from a fluomine-based concept to molecular sieve-based oxygen generation.

Membrane Permeation

Membrane permeation as a means of onboard generation of aviator's breathing oxygen was investigated by AiResearch in 1979, under a contract sponsored by the United States Air Force (12). The hope was to exploit the possibility of using a single process for gas separation to provide a nitrogen-rich, oxygen-deficient gas for fuel tank inerting while, at the same time, providing an oxygen enriched gas for breathing. Figure 3.5 shows a test module for the permeable membrane oxygen generating system. The membrane material was fabricated in the form of hollow fibers, spun from DX-810 grade poly 4-methyl-1-pentene. Each fiber had a nominal internal diameter of 30 µm and wall thickness of 6 µm. The fiber bundle contained approximately 510,000 fibers of nominal 170 mm active permeating length. The module itself was a lucite cylinder 83 mm in diameter capped with two 38 mm thick aluminum end plates. The hollow fiber bundle was actually made from a single fiber wound around the two end plates in a manner similar to a filament-winding process. A bonding agent was then applied to the tube sheet at each end of the unit, and the loops at the end of the fibers

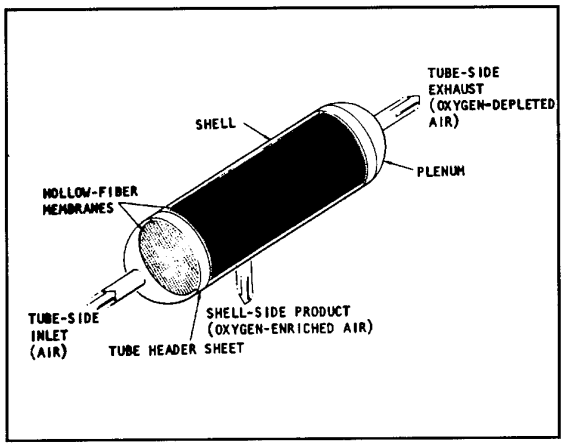

Fig. 3.5 Hollow fiber membrane permeation test module.

severed to form manifolded, parallel tubes. The resulting structure was similar to that of a shell and tube heat exchanger.

When pressurized air was applied to one end of the module, the waste gas eluting at the end of the tube bundle contained approximately 9% oxygen-91% nitrogen, a gas mixture considered suitable for fuel tank inerting. The oxygen-rich product gas eluting from the shell side of the module contained approximately 50% oxygen-50% nitrogen. The oxygen concentration of the shell side stream could be further increased by adding a second concentration stage or by refluxing a portion of the oxygen-rich product to mix with and enrich the feed air. Both procedures, however, required interstage compressors to maintain the flows and pressures required. The cascade system produced a successively enriched oxygen product at each stage, but introduced a considerably greater overall feed-to-product flow ratio, in addition to the need for interstage compression. The reflux system had the benefit of reducing the feed to product flow ratio, and increasing the product oxygen concentration at each stage. However, the oxygen concentration in the nitrogen-rich product was also increased, thereby requiring additional staging of the tube side gas if it was required for fuel tank inerting.

The overall conclusion from the membrane oxygen system feasibility study was that a membrane system would be most applicable in aircraft designed to fly at altitudes less than 25,000 feet, where a single stage system, perhaps with product reflux could be employed. While a dual function system appeared feasible, the gas flow requirements for fuel tank inerting for most turbine powered aircraft are 100 to 1000 times greater than the gas flow requirements for human breathing. Hence the fuel tank inerting requirements will largely dictate any future system design.

Pressure Swing Adsorption (Molecular Sieve)

The molecular sieve behavior of crystalline zeolites and their large potential in performing molecular sieving separations was first demonstrated in the pioneering work of Barrer and colleagues in Great Britain (4). With the commercial production of synthetic zeolites in 1954, a new class of molecular sieve materials became available, capable of being tailor-made in terms of structure, composition and properties. The current technology of pressure swing adsorption for air separation was developed by Skarstrom in the late 1950's (18). The first application of molecular sieves for onboard generation of breathing oxygen in aircraft appears to have been about 1972 when Litton Instruments and Life Support Division (then Bendix Corporation), Davenport IA, employed pressure swing adsorption (PSA) as a preliminary oxygen enrichment step in the development of the barium oxide-based (Brin process) oxygen generation system . This early PSA system was optimized for adsorption of carbon dioxide, and produced an enriched air product in the range from 50 to 70% oxygen. Although the barium oxide system did not survive to flight test, Litton continued development of the PSA process, and in 1977, offered an improved molecular sieve oxygen concentrator capable of delivering up to 95% oxygen. This system was accepted by the U. S. Navy for flight test in the EA-6B aircraft (7). At the completion of the EA-6B demonstration project, the U. S. Navy initiated development of a molecular sieve oxygen generation system (MSOGS) for the AV-8A Harrier aircraft, a program which resulted in modification of six AV-8A aircraft for extended operational test and evaluation between 1977 and 1980 (9). The production version Litton AV-8 concentrator is fitted to the joint United States Navy-United Kingdom advanced Harrier aircraft (AV-8B and Harrier GR Mk5 aircraft, respectively). The MSOGS fitted to the USN AV-8B includes a simple pressure demand regulator which delivers product gas containing a typically high concentration of oxygen. The UK Harrier GR Mk5 MSOGS employs a British flow controller to increase the flow of product gas thereby reducing the concentration of oxygen in the gas delivered to the pilot. A similar approach was employed in the 1981 USAF advanced development program conducted by General Dynamics for the F-16A aircraft. A Litton molecular sieve oxygen concentrator, flow controller, and regulator, with a backup supply system were designed for the F-16A aircraft (11). The MSOGS was successfully test flown on an F-16A aircraft from 1982 through 1985. The system may be incorporated into future upgrades of the F-16 aircraft. Normalair-Garrett Ltd in the United Kingdom commenced development in the mid-1970s of a three-bed molecular sieve oxygen concentrator with closed loop control of the concentration of oxygen in the product gas, and a low inlet pressure demand regulator. One development of this MSOGS designed for use in fighter aircraft was flight tested in the RAF Institute of Aviation Medicine's Hunter T7 aircraft in 1982 (2). Normalair-Garret Ltd molecular sieve oxygen concentrators are incorporated in the MSOGS of the B-1B bomber aircraft, and in the UK Experimental Aircraft Program (see Chapter 8).

AIR INDEPENDENT OXYGEN SYSTEMS

Water Electrolysis System

The water electrolysis oxygen generation system was developed by TRW Equipment Laboratories, Cleveland Ohio, under contract to NASA (3). The partially closed system (Figure 3.6) consisted of a rebreather loop through an electrochemical carbon dioxide concentrator to remove carbon dioxide, moisture and heat from expired breathing gas. Makeup oxygen, obtained from a water electrolysis unit, was added via demand regulator. Water electrolysis was specifically selected to make the system independent of air source

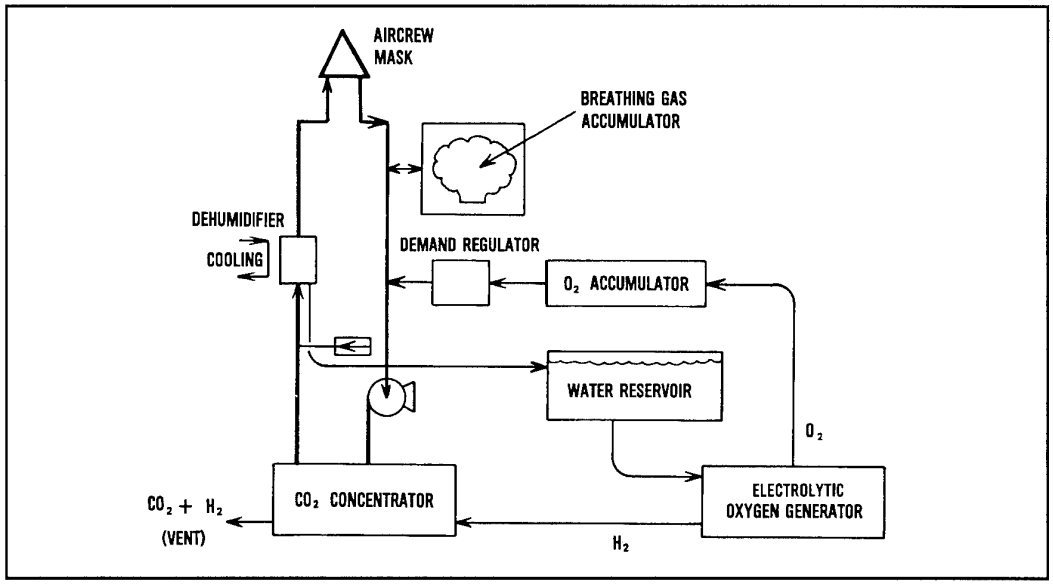

Fig. 3.6 Flow schematic of partially closed-loop water electrolysis oxygen generating system with electrochemical carbon dioxide concentrator.

for either high altitude or space applications.

The water electrolysis module employed polysulfone cells with KOH electrolyte held in a porous asbestos matrix between platinumized electrodes. The carbon dioxide concentrator consisted of porous electrodes separated by an asbestos capillary matrix containing an aqueous solution of cesium carbonate ($CsC0_3$). Waste hydrogen from the water electrolysis module was fed to the carbon dioxide concentrator, thereby permitting the concentrator to be operated in the hydrogen depolarized mode. In this manner, the carbon dioxide concentrator operated as a fuel cell and had the capability of supplying power to other portions of the life support system if desired. A breadboard version of the electrolytic oxygen generating system was flight tested in a U. S. Navy C-131F aircraft at the Pacific Missile Test Center, Point Mugu, California in the summer of 1969. A total of five flight tests were accomplished accumulating 14.85 hours of oxygen system operation. The oxygen generating unit occupied a volume of 0.27 cubic meters and weighed approximately 15 kg. It produced oxygen at a maximum rate of 1.1 L (NTPD) min^{-1} at a power consumption rate of about 600 watts.

Because of the high power requirement, further development of the electrolytic oxygen generation system was largely abandoned, although the air independent feature made it potentially attractive for future spacecraft or transatmospheric vehicle application. The major conclusions emanating from the flight test program were the need for high purity makeup water to prevent damage to the water electrolysis cell, and the need to maintain water balance in the carbon dioxide concentrator.

Alkali Metal Chlorate (Chlorate Candles)

The decomposition of sodium or potassium chlorate, in the presence of a reducing agent such as carbon or powdered metals, is commonly employed in the laboratory to generate oxygen. The application of alkali metal chlorates to aircraft oxygen supply systems was an outgrowth of World War II technologies (17), and today "solid chemical" oxygen storage systems are used for emergency passenger oxygen on many commercial airliners.

A typical chlorate oxygen generator is shown schematically in Figure 3.7. Solid chemical oxygen cartridges can be

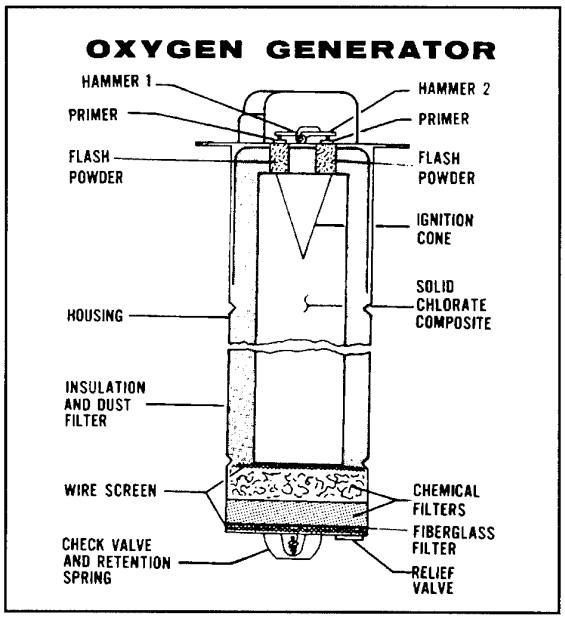

Fig. 3.7 Solid chemical (Sodium Chlorate) oxygen generator.

design tailored for almost any flow rate in the range from 1 to 100 L (NTPD) min^{-1}. The advantage of solid chemical systems is their long shelf life and the freedom from frequent maintenance that characterizes the use of either high or low pressure gaseous oxygen systems. Solid chemical oxygen generators are not generally practical for routine oxygen supply for aircrew, however, because the cartridges

are relatively expensive and not regenerable except by replacement. Nonetheless, chlorate systems have been developed which have the capability of providing sufficient oxygen for several aircrew for several hours at moderate altitudes.

Alkali Metal Superoxides

Potassium superoxide (K_2O_4), is a stable, canary yellow solid, that when treated with water, liberates oxygen and forms caustic potash (KOH). This reaction forms the basis for the use of potassium superoxide (tetroxide, peroxide or dioxide) in self-contained breathing escape devices and respirators of the "rebreather" type which operate under "lung" power. The moisture of the breath reacts with the superoxide to generate oxygen, and the potash which is produced reacts with expired carbon dioxide to form potassium carbonate. More recent studies have been conducted on mixtures of potassium and calcium superoxides to improve both the efficiency of oxygen generation and the oxygen/carbon dioxide exchange ratio (19).

SUMMARY

While a number of chemical processes have been investigated for generation of aviator's breathing oxygen onboard, in-flight, the emerging system of choice is clearly the molecular sieve concept employing pressure swing adsorption on synthetic zeolites which may include carbon, as well as aluminosilicate molecular sieves. The PSA concept has the advantage of simplicity, small size, low weight and power requirement, minimal cost, and broad application for tactical, strategic, and training/airlift aircraft with up to ten crewmembers. It's principle disadvantage of producing less than 100 percent oxygen can be overcome by the relatively simple expedient of adjusting the pressure delivery schedule of the breathing regulator, when this is required for hypoxia protection at high altitude.

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Chapter 4

OPERATIONAL REQUIREMENTS FOR AND MAJOR DESIGN FEATURES OF ADVANCED OXYGEN SYSTEMS

John B. Tedor

INTRODUCTION

Operational deployment of advanced oxygen systems will benefit the user in three important ways: improved crew comfort, protection, and performance; significant reduction of life cycle cost; and increased combat capability. An ideal breathing system for military aircraft would: (i) keep the crew comfortable and fully protected against all potential adverse respiratory conditions, (ii) automatically adjust to changing environmental conditions and emergency situations without requiring crew input, (iii) be inexpensive to buy and install, and (iv) always be ready to support a combat mission without any maintenance or logistic support requirements. No oxygen system currently built or envisioned fulfills all these ideals. But several new advanced oxygen system designs are a quantum improvement over the comparatively primitive oxygen supply systems currently installed on most military aircraft. In spite of dramatic improvements in aircraft performance over the last four decades, it is only recently that more advanced oxygen systems have been adopted by many Air Forces.

OPERATIONAL NEEDS

Aircrew

Aircrew need clean, physiologically adequate breathing gas. The operational speed, altitudes and accelerative forces of modern high performance military aircraft can subject aircrew to severe discomfort and extreme physiologic stresses, which potentially can result in incapacitation or death. Classic World War II-type oxygen equipment furnishes some protection against the physiological stresses of high altitude and rapid decompression. However, this protection is limited to about 50,000 feet maximum altitude, and may require operator intervention to adjust the system. Furthermore, conventional oxygen systems provide the crew no assistance in countering the adverse cardio-pulmonary effects of high-G maneuvers. In addition, current systems do not furnish adequate protection against potential contamination of the breathing gas, which may now include chemical warfare agents in addition to more common cockpit smoke and fumes. The oxygen may be contaminated either during its production and storage, or as it is breathed through a dilution device which entrains outside air.

Logisticians

Logisticians require reliable, inexpensive, easy to support aircraft subsystems. Logistic support and maintenance outlays are major contributors to life cycle cost. Today's oxygen systems require replenishment of consumed liquid or gaseous oxygen stores either daily or sometimes, after every flying mission. This imposes a heavy logistics penalty, not only for the consumable itself, but also for the manpower required for ground support. This cumbersome logistical tail is exceptionally vulnerable in wartime. In addition, liquid oxygen or high pressure cylinders are hazardous materials which, if not handled properly, can cause damage to expensive aircraft and potential loss of life. Lastly, although conventional oxygen systems are simple in design, both liquid oxygen converters and breathing regulators require frequent maintenance and refurbishment to insure proper function.

Commanders

Every commander needs the increased combat capability which can be afforded by advanced oxygen systems, through lower life cycle costs, reduced maintenance, and minimal logistic support. These features result in less "down time" for aircraft, quicker turnaround during sortie surge, and easier dispersion to remote sites. Minimal crew attention required for the breathing system can improve focus on the mission at hand. Increased aircrew comfort and protection will improve crew performance throughout the flight envelope.

OPERATIONAL CHARACTERISTICS AND DESIGN FEATURES

Physiological Sufficiency

The foremost operational characteristic of the oxygen system is that it satisfies the physiological breathing requirements of the crew. Design features which promote this characteristic include: (i) filtration capacity and oxygen concentration control, (ii) adequate system flow capacity, (iii) minimal resistance to breathing, (iv) provision of appropriate pressure breathing, and (v) personal equipment (e.g., oronasal mask) to supply the gas to the crewman at the required flow rate and pressure.

The oxygen system must furnish a clean, odorless, nontoxic, breathable gas with a partial pressure of oxygen sufficient to protect the crew against both steady state hypoxia at the current cabin altitude and the transient hypoxia that may follow rapid decompression at high altitude. Ideally, the oxygen partial pressure will be at least equivalent to sea level, but not so high as to cause oxygen toxicity, acceleration-induced atelectasis, or delayed barotitis media.

The oxygen system must supply sufficient flow of breathing gas to meet the respiratory minute volume requirements of the crew, and the transient peak flow demands during maximal respiratory effort. In addition, it should deliver these flows at breathing pressures that do not impose excessive impedance to breathing. Finally, the breathing gas must be delivered at the appropriate positive breathing pressure following decompression to high altitude, or under G-loading if the system is designed to provide pressure breathing in response to +Gz acceleration (2).

Man-Machine Interface

Design features supporting the characteristic of a simple

man-machine interface include human engineered controls and displays, and automated emergency functions. It is important that the system interface be as simple as possible, yet give the crewmember complete, flexible control of breathing gas delivery. Control switches, indicators, and warning devices associated with the oxygen system must be readily visible to the crew in their normal cockpit positions, and must be clearly labelled and readable. Switches should be within reach from normal cockpit position, even under adverse G-loading conditions. Critical system activities (e.g., switching to backup oxygen on failure of primary breathing gas source or on rapid decompression, application of pressure breathing and associated mask tightening) must occur automatically without crew action. Nevertheless, capability to initiate or override these functions manually should be available as well, to provide full operational flexibility.

Logistics Support

Advanced oxygen systems require minimal logistic support; i.e., aircrew breathing gas is generated onboard the aircraft. Onboard oxygen generation eliminates the requirement for replenishment of stored oxygen and the associated ground support costs, vulnerabilities, and hazards. Furthermore, the system and each of its components must be designed for high reliability and minimum maintenance. The system should incorporate features such as line replaceable units (LRUs) and easy access to all components so that skill and time required for any maintenance action are minimized. Application of the principles of simplicity, commonality, and ruggedness help to achieve these reliability and maintainability goals. The operational characteristic of minimal logistic support results in an advanced oxygen system with lower life cycle cost. Design features supporting this characteristic are onboard breathing gas production, application of reliability/maintainability techniques such as failure mode analyses, and incorporation of built-in-test (BIT) and press-to-test (PTT) functions.

System Safety

Safe operation is another vital characteristic of advanced oxygen systems. The breathing system must pose minimal hazard to aircrew using the system and groundcrew servicing it. System safety is enhanced by employing hazard analysis and hazard reduction strategies during system design. Incorporation of redundancy at critical points, and the use of fail-safe design strategies will prevent unsafe conditions and catastrophic failure. Special attention must be given to emergency and escape situations, as they impose additional requirements and constraints on the breathing system. Design features promoting system safety include hazard reduction measures and provision for emergency oxygen supply with automatic, fail-safe activation.

ADVANCED OXYGEN SYSTEM (AOS) ELEMENTS

Certain basic elements are common to all advanced oxygen installations. These include: the breathing gas source, oxygen generator, distribution system, breathing regulator, personal equipment, controls and displays, and emergency/back-up oxygen.

Breathing Gas Source

In current AOS designs, the primary source of breathing gas is engine bleed air. In most turbine-driven aircraft, bleed air is readily available at temperatures and pressures which can be conditioned to a range appropriate for oxygen concentration. Usually both cooling and pressure reduction are required, but bleed air from small, low power engines may require additional compression. In some installations, bleed air from already conditioned environmental control system (ECS) lines may be tapped directly to an oxygen concentrator. The breathing system consumes only one or two pounds of air per person per minute (much less is actually consumed by the crew member). This amount is miniscule compared to the throughput of modern turbine engines. While air consumption for the breathing system will almost never impact engine design, an ECS overburdened with avionics cooling requirements may not have excess capacity for OBOGS. Therefore, breathing system air demand should be minimized and considered in ECS design criteria.

Oxygen Generator

Various oxygen separation/concentration techniques have been described in Chapter 3. In air dependent oxygen systems, the generator may be thought of as a separator, separating oxygen from nitrogen and other components of air, or a concentrator, increasing the fractional oxygen content of the air it processes. Although several types of systems have been demonstrated in the laboratory, only the fluomine and molecular sieve concepts have been fully flight qualified.

Molecular sieve concentrators may be designed to produce breathing gas with oxygen content in a given control range, or more simply to produce an optimal concentration based on demand flow, input air temperature and pressure, and exhaust pressure. Sizing the concentrator is an important factor in system design because product gas oxygen concentration is a strong function of demand flow as a fraction of total concentrator throughput capacity. Maximum oxygen concentration achievable with present molecular sieve systems is about 95%. The remaining 5% of the product gas is primarily argon which can not be effectively separated from oxygen without secondary purification (using carbon molecular sieves) with attendant penalties in throughput and system complexity.

Distribution System

The output of the oxygen generator enters the distribution system for delivery to each crewmember position. The pipework may be short or long, depending upon location of the concentrator in relation to the crew compartment and routing of the tubing through the airframe. Size (diameter) of the pipework is an important design consideration. Molecular sieve concentrator output pressure is typically low [about 25 lbf in^{-2} gauge (172 kPag)] in comparison to conventional oxygen systems. Even at engine idle, product gas must reach the breathing regulator(s) with sufficient pressure to drive regulator functions [minimally about 10 lbf in^{-2} gauge (69 kPag)]. Therefore, large bore tube may be required to minimize distribution line pressure drop at maximum demand flow, particularly in long, twisting tubing runs. The distribution system may include a plenum to modulate demand on the concentrator and dampen system pressure excursions. On-off valves, check valves, quick disconnects,

and other pipework items are also part of the distribution element.

Breathing Gas Regulator

The distribution system supplies breathing gas to each crew station where a breathing regulator controls pressure and flow delivery to the crewmember, based upon the regulator mode selected, current environmental conditions (cabin altitude and perhaps G-loading), and the crewmember's respiratory demand. The regulator may be panel mounted, chest (harness) mounted, or ejection seat mounted. Seat mounting is the preferred position because it frees panel space, and the regulator can accompany the pilot in case of ejection at altitude. Seat mounting also results in less mishandling and allows larger, more rugged construction than harness mounting.

A non-dilution type of regulator is preferred, although some advanced systems incorporating dilution devices have been developed. Non-dilution maintains the integrity of the oxygen system, reducing the likelihood of toxic contaminant entry, taking advantage of molecular sieve concentrator's inherent filtration capability, and allowing concentration control at the point of breathing gas generation. Non-dilution regulators are also simpler to build and more reliable because of fewer failure modes.

The regulator must operate at low inlet pressure in view of the low concentrator output pressure. It must also provide high flow capacity to meet physiological demand with minimal impedance. In an AOS specifically designed for high altitude (>50,000 feet) or high G-loading environments, the regulator should communicate in some way (pneumatically, electrically, or mechanically) with the anti-G valve. This communication permits proper ratios between breathing pressure/torso counterpressure and lower body counterpressure applied by anti-G trousers for high altitude protection or while pressure breathing during G-loading. Some AOS designs include a redundant regulator package because of the critical nature of the breathing regulator and its potential complexity.

Personal Equipment

From the regulator, breathing gas passes directly to the aviator's personal breathing equipment, which consists of at least an oronasal mask. Other crewmember-mounted items may include a personal equipment connector (PEC), torso counter pressure vest, pressure breathing helmet, and chemical defense respirator/filter assembly. For an AOS to provide full expansion of operational capabilities, these optional items must become part of the system for altitude, anti-G, and chemical defense protection. The PEC provides a rapid, fail-safe single point connection and release mechanism for all aircrew personal life support and communications equipment.

The counterpressure vest, in conjunction with a high pressure mask/helmet assembly and anti-G suit inflation, permits assisted positive pressure breathing up to 75 mm Hg (10 kPag) mask pressure for short time periods. Such ensembles have been shown to provide effective "get-me-down" protection from altitudes as high as 60,000-65,000 feet (1). Assisted positive pressure breathing is also an effective method of enhancing tolerance to high sustained +Gz acceleration (2). The pressure mask/helmet assembly should include automatic mask tightening capability. Aircrew eye, head, and respiratory protection would be required during threat of chemical attack.

Controls and Displays

Controls, indicators, and warning/display functions of an AOS should be considered as a separate element because they form an important man-machine interface. The value of simple, straightforward controls and displays has been mentioned already. In addition to visual indicators, useful aural and tactile cues to system status (e.g. a warning tone, click, or buzz; switch positions, locking mechanism indicators) should not be overlooked, provided they can still be heard in the cockpit noise environment or perceived with a gloved hand.

Emergency/Backup Oxygen

Emergency/back-up oxygen may be ejection seat or airframe mounted. Seat mounting gives the advantage of accompanying the pilot during escape at altitude, but limits the size and weight of the emergency assembly. For adequate altitude protection, however, at least a small portion of the emergency supply must be seat or harness mounted. Present systems use ground refurbished gaseous oxygen, which requires additional logistic support. Some advanced oxygen systems include the automatic refilling of the back-up oxygen supply in flight. Besides the redundant oxygen supply itself, the emergency assembly includes a release or selector valve to permit manual or automatic activation of the alternate gas source. Generally emergency oxygen is activated above a preset cabin altitude or in case of primary breathing gas failure.

SUMMARY

Many deficiencies of current aircraft breathing systems can be overcome by the use of state-of-the-art onboard oxygen generation technology, updated breathing regulator designs, and new personal equipment. Careful integration of the elements of an advanced oxygen system will form the cornerstone of a fully integrated life support system, wherein maximal crew protection against the hazards of altitude, G-forces, toxic chemicals, emergency escape, thermal stress, and other features of the aircraft combat environment can be assured with limited burden to the aircrew and minimal logistic costs. Such systems promise operational commanders better utilization of present and future high performance aircraft, with significant increases in combat capability.

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Chapter 5

PHYSIOLOGICAL REQUIREMENTS FOR ADVANCED OXYGEN SYSTEMS

John Ernsting

INTRODUCTION

The performance of an aircrew breathing system for a high performance combat aircraft should be such that it imposes minimal physiological stress on the aircrew member in any circumstance either on the ground or in flight. Some compromise is necessary, however, in order to avoid undue complexity and financial cost. The practical compromises which have led to the current standards for the performance of the breathing gas systems of high performance combat aircraft are described in this chapter.

RESPIRATION IN FLIGHT

Knowledge of the pulmonary ventilation and the peak respiratory flows demanded by aircrew in flight and on the ground are of vital importance to the specification of the performance required of an aircrew breathing system. Thus the magnitude of the pulmonary ventilation under various conditions of flight which will allow the estimation of the pulmonary ventilation averaged over the portions of the sortie is essential for the calculation of the size of the back-up and emergency oxygen stores. Knowledge of the range of pulmonary ventilation which may be demanded by the crew over relatively short periods of flight (30 sec or so) is required for the specification of the performance of molecular sieve oxygen concentrator systems. Finally the impedance to respiration imposed by any breathing system is a function of the instantaneous inspiratory and expiratory flows created by the aircrew.

Average Pulmonary Ventilation

Only a small number of studies have been made of the pulmonary ventilation of aircrew operating high performance combat aircraft. Experience of the inadequacy of basing the quantity of oxygen to be carried in an aircraft upon an earlier standard of 14.5 L (BTPS) min^{-1} for the pulmonary ventilation averaged over the whole sortie, the United Kingdom (UK) made an extensive series of measurements of bottle oxygen consumption in a wide variety of combat aircraft. These measurements led to the adoption in the early 1960s of a pulmonary ventilation of 23 L (BTPS) min^{-1} for predicting the oxygen consumption of the pilot of a single seat combat aircraft (to include 97% of occurrences)(8). The corresponding pulmonary ventilation per man for two or three crew aircraft was 19.7 L (BTPS) min^{-1}, and for four or more crew aircraft was 17.1 L (BTPS) min^{-1}. Extensive experience over the subsequent 30 years operating aircraft in which the quantity of oxygen carried was based on these latter figures has confirmed their adequacy.

A preliminary study of pulmonary ventilation of 12 RAF pilots during aerobatic flight in a Hunter T7 aircraft simulating air combat manoeuvres conducted in 1975 (34) yielded a mean pulmonary ventilation [sustained for one minute] of 26 L (BTPS) min^{-1} with a range of 19 to 55 L (BTPS) min^{-1}. Another preliminary study reported by the USAF School of Aerospace Medicine in 1977 (35) also suggested that high levels of pulmonary ventilation could occur in specific phases of flight, particularly air combat manoeuvring.

The USAF requirements for the quantity of oxygen to be carried in aircraft were revised and published in 1978 in a new edition of a Military Standard (47). This revision recognised the increase of pulmonary ventilation which occurs in specific phases of flight. It employed baseline pulmonary ventilations for calculation of the ventilation averaged over the whole sortie of 18.0 L (BTPS) min^{-1} for a single pilot and 16.5 L (BTPS) min^{-1} for each of a two man crew. The revised specification stated that this baseline pulmonary ventilation is increased by 75% in aerial combat and by 25% by terrain following. Assuming that the pilot will be involved in air-to-air combat for one third of a sortie, the pulmonary ventilation meaned over the whole sortie predicted by the US Military Specification (47) is 22.5 L (BTPS) min^{-1} which is very similar to the 23.0 L (BTPS) min^{-1} employed in the present UK military standard (8). The very extensive study of 18 pilots flying a fast jet in simulated air combat and other aerobatic manoeuvres performed by Harding (22) yielded a mean pulmonary ventilation averaged over all sorties of 18.8 L (BTPS) min^{-1}. Calculations suggest that the value of pulmonary ventilation which would include 97% of these flights was of the order of 24 L (BTPS) min^{-1}.

Minimum and Maximum Pulmonary Ventilation

The minimum and the maximum levels of pulmonary ventilation which may be sustained in flight are of considerable importance in the design of molecular sieve oxygen concentrator systems as in such systems the concentration of oxygen in the product gas varies inversely with the demand. In this context "sustained" is the pulmonary ventilation which is maintained for a period of 30 sec or longer. The minimum pulmonary ventilation which will occur during undisturbed straight and level flight is very similar to the minimum seen in subjects seated at rest on the ground i.e., 6.0 L (BTPS) min^{-1}.

There have been a limited number of studies of the maximum levels of pulmonary ventilation which occur in flight. The data collected on 12 test pilots by Macmillan et al. (34) yielded a maximum sustained (30 sec) ventilation of 51 L (BTPS) min^{-1}. A value in excess of 40 L (BTPS) min^{-1} was only recorded on 1.6% of occasions. The more extensive study performed using a breathing system with a very low resistance of pilots carrying out simulated aerial combat and other manoeuvres gave a maximum sustained pulmonary ventilation of 44 L (BTPS) min^{-1} (22). The ventilation recorded in these flights exceeded 40 L (BTPS) min^{-1} on less than 1 - 2% of occasions even during air combat manoeuvring. The standard adopted by the ASCC and NATO nations for the maximum pulmonary ventilation which can be sustained in flight for 30 sec or more is 50 L (ATPD) min^{-1} (2, 37). [It is convenient to specify flow requirements for breathing systems under ATPD rather than BTPS conditions, the former being 84-87% of the latter at normal cabin altitudes in combat aircraft].

Instantaneous Respiratory Flow

The instantaneous flow of gas into and out of the respiratory system is one of the principal factors which determine the magnitude of the changes in mask pressure imposed by a breathing gas system, the other being the pressure-flow characteristics of the breathing equipment itself. Of particular significance are the maximum (peak) inspiratory and expiratory flows which occur during the respiratory cycle. One of the earliest and most extensive experimental studies of instantaneous respiratory flows at rest and during exercise and the effects of various levels of resistance to gas flow upon them, was that conducted by Silverman and his colleagues in World War II (46). They produced invaluable information on the variability of respiratory flow patterns, both with time, subject and level of physical exercise and of the effects of external resistance upon pulmonary ventilation and peak respiratory flows. They showed that although for some purposes respiratory flow can be assumed to follow a sine curve [when the peak flow is given by Π times the pulmonary ventilation], the peak inspiratory flow at rest is typically 3.2-3.8 times the pulmonary ventilation whilst the peak expiratory flow is about 2.7-3.0 times the pulmonary ventilation. Respiratory flow patterns tend to become more regular with physical exercise. Respiratory flow patterns are greatly modified in speech when the peak inspiratory flow is increased to 5-10 times the pulmonary ventilation (9). Large changes in flow patterns are also produced by the Anti G Straining Manoeuvre (AGSM) when the durations of inspiration and expiration are greatly reduced and peak flows are increased to between 7 and 15 times the pulmonary ventilation. Pressure breathing without external counterpressure also produces marked changes in the respiratory flow pattern (13). The application of adequate counterpressure to the chest and abdomen, however, virtually restores the respiratory flow pattern to that which occurs in light exercise. The flow patterns during pressure breathing with $+G_z$ acceleration (PBG) with counterpressure applied to the chest and abdomen are also similar to those produced by mild exercise provided that the subject does not perform any respiratory straining manoeuvre.

There have been several valuable studies of the respiratory flow patterns of aircrew during flight (34, 22, 18). Most of these have been performed with the aircrew using standard pressure demand oxygen delivery equipment; one (22), employed a special-to-task low resistance breathing system. The highest instantaneous flows occurred during air combat when employing the AGSM to increase tolerance of $+G_z$ acceleration. High peak inspiratory flows are also recorded during speech. Inspiratory and expiratory flows were also high immediately after entry into the cockpit due to the effort expended in climbing into the aircraft and connecting the harness and personal services. The peak inspiratory flows recorded in flight are affected by the flow capacity and the resistance to respiration of the breathing system employed in the study. Thus the highest peak inspiratory flows recorded in the study using a standard panel mounted pressure demand regulator was 160 (ATPD) min^{-1} (34), whilst peak flows of up to 385 L (BTPS) min^{-1} were recorded in the flight study in which the low resistance breathing system had a flow capacity considerably in excess of 600 L (ATPD) min^{-1} (22). Even with this very low resistance breathing system, only 2.5% of all the breaths recorded had a peak inspiratory flow greater than 220 L (BTPS) min^{-1}. Similar results were obtained in the study conducted by Gordge (18) of aircrew operating F-14, F/A-18, A-7 and A6 aircraft. He found that 2.4% of breaths had peak inspiratory flows exceeding 200 L (ATPD) min^{-1}. The breathing systems of high performance aircraft in which aircrew will be exposed to $+G_z$ accelerations and in which they will perform air combat manoeuvring should ideally be capable of meeting inspiratory and expiratory flows of up to 250 L (ATPD) min^{-1}. Present ASCC and NATO specifications (2, 37) require that aircrew breathing systems are capable of meeting peak inspiratory and expiratory flows of at least 200 L (ATPD) min^{-1}.

In most pressure demand breathing systems, the impedance to respiration imposed by the system is a function not only of the instantaneous respiratory flow but also the rate of change of flow. The rates of change of flow which occur during breathing are related to the nature of the respiratory manoeuvre eg. quiet breathing, speech, AGSM, pressure breathing and, to a limited extent, to the peak respiratory flow. Thus speech at rest increases the median rate of increase and decrease of inspiratory flow during quiet breathing from 1.6 sec^{-2} to 18 L sec^{-2} (9). In practice, the highest rates of change of flow occur in speech and whilst performing the ASGM. The minimum rates of change of inspiratory and expiratory flow [over 90% of the flow range] specified by current ASCC and NATO requirements (2, 37) for aircrew breathing systems are 10 L (ATPD) sec^{-2} at a peak flow of 90 L (ATPD) min^{-1}, increasing to 20 L (ATPD) sec^{-2} at a peak flow of 200(ATPD) min^{-1}.

Of interest in dual seat combat aircraft are the relationships between the breathing of the two crew members. Monte Carlo simulation of the inspiratory demands of two crew members suggests (4) that 95% of all instantaneous peak demand flows can be met by a breathing system which will provide 70% of the flow demanded when the two crew members are breathing exactly in phase. An in-flight study (23) in which the inspiratory flow patterns of the two crew of a Hunter T7 were recorded during level flight, high G aerobatics and simulated combat manoeuvring, showed that the beginning of inspiration occurred simultaneously in the two pilots in less than 1% of 5,000 breaths. The present UK Standard (8) requires that a breathing system for two crew members provides 85% of the peak inspiratory flow which could be demanded by both crew members breathing exactly in phase.

RESISTANCE TO RESPIRATION

Effects of external resistance

Excessive external resistance to breathing can give rise to breathing discomfort, fatigue of the respiratory muscles, to changes in lung volumes and pulmonary ventilation, generally hypoventilation but on occasions hyperventilation (11). Excessive resistance also impairs speech and the ability to perform the ASGM. Finally, changes in the mean intrapulmonary pressure induced by external resistances can disturb the cardiovascular system and the distribution of body fluids. One of the earliest studies of the effects of added external resistances performed by Haldane et al (7) found that respiration was slowed and the alveolar PCO_2 raised when the pressure swing at the lips exceed about 5 inch wg (1.25 kPa). A doubling of this pressure swing occasionally produced rapid shallow breathing. Killick (30) also found that inspiratory resistance generally reduced pulmonary ventilation and that the intensity of the distress was related to

the retention of carbon dioxide. Some of her subjects, however, hyperventilated in response to the imposition of inspiratory resistance. The subjective effects of external resistances were studied extensively by Hart (24). He introduced simple orifice restrictors in each and both phases of respiration, in subjects at rest and during moderate exercise. He asked the subjects, after a short period of exposure, to report whether the resistance was unnoticed, noticed but not uncomfortable (light resistance), not uncomfortable for a short period but would become so in 10-30 minutes (moderate resistance), and uncomfortable and too high even for a short period (heavy). The results obtained for resistances imposed in inspiration are summarised in Figure 5.1. Hart found that the sensations produced by resistance imposed in expiration were similarly related to the relationship between peak expiratory flow and pressure. The value of Hart's studies was limited by his use of simple orifices and the short time for which the subjects were exposed to each level of resistance.

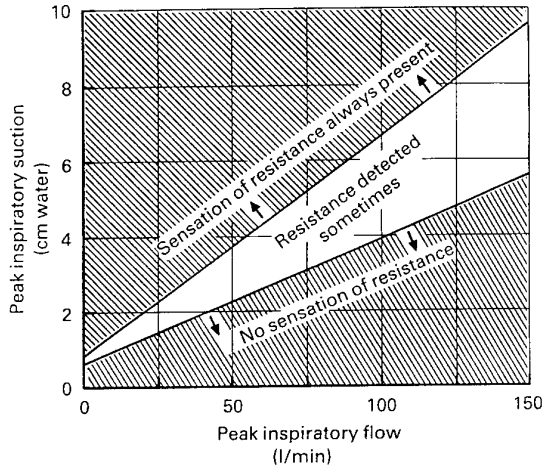

Fig. 5.1. The relationships between peak inspiratory flow and peak inspiratory suction which give rise to sensations of resistance to breathing based upon the studies of Hart (24).

An extensive study using large groups of subjects seated at rest and carrying out exercise on a bicycle ergometer was conducted by Silverman et al. (46) who investigated the effects over periods of 45 minutes of introducing linear resistances [pressure drop directly proportional to flow] in each and both phases of respiration. They determined the effects of the added resistances on respiratory flow patterns, pulmonary ventilation, oxygen consumption and recorded the comments of their subjects. They found that added external resistance caused a reduction in pulmonary ventilation and respiratory frequency; that a high expiratory resistance decreased oxygen consumption; that subjective discomfort occurred when the inspiratory resistance was less than the expiratory resistance and both were greater than 2 inch wg (0.5 kPa) at a flow of 85 L (ATPD) min^{-1}; and that the physiological and subjective disturbances produced by resistances were less marked in those trained in physical work or respiratory resistance. They also found that in about 10% of their subjects, the addition of resistances of this order caused an increase in pulmonary ventilation and hypocapnia. Silverman et al. (46) recommended that the resistance imposed by breathing equipment at respiratory flows of 85 L (ATPD) min^{-1} should not exceed 2.5 inch (0.63 kPa) during inspiration and 2.1 inch (0.45 kPa) during expiration.

Silverman et al. (46) also calculated the external work of breathing for each of the resistances which they employed. They suggested that the allowable rate of external respiratory work was a linear function of the total body work and they concluded that external respiratory work should not exceed 0.6% of the total body work. Cooper, who found an error in their calculations of external respiratory work, revised this figure to 0.74% of the total body work (6). Cooper proceeded to propose that external respiratory work imposed by breathing equipment should be expressed as work per litre of pulmonary ventilation. He concluded from his own studies and those of Silverman that the maximum tolerable external respiratory workload above which serious discomfort and physiological disturbances will occur is 0.25 kgm L^{-1}. Cooper recommended (6) that in order to ensure comfortable breathing at rest and during exercise the external work should not exceed 0.125 kgm L^{-1}.

An analysis by Morrison and Reimers (36) of studies performed on the acceptability of resistances imposed by breathing equipment employed in mine rescue and diving (3), led to the conclusion that the allowable external work per litre of pulmonary ventilation proposed by Silverman (46) and Cooper (6) were too high at low levels of ventilation. They advocated that the external work should not exceed [0.002 x pulmonary ventilation (L (ATPD) min^{-1}) + 0.05] kgm L^{-1}. This limit will maintain external work within the limits of comfort as reported by a wide range of physiological studies including those of Hart (24), Silverman et al. (46), Bentley et al. (3), and Morrison and Reimers (36).

Resistance imposed by aircrew breathing systems

The resistance to respiration imposed by many current conventional pressure demand oxygen systems is excessive, especially when high flows are demanded from the system as during speech, air combat and during head movements which change the volume of the inlet hose to the mask (Chapter 2 refers). Although ideally an aircrew breathing gas system should not impose any resistance to respiration this situation cannot be achieved in practice. The practical compromises which can and should be achieved in an aircrew breathing system are outlined in the following paragraphs.

The resistance to respiration imposed by a breathing system can best be defined in terms of the relationships between the pressure in the cavity of the mask and the corresponding respiratory demands. It is generally most appropriate to relate the minimum and maximum mask pressures during the respiratory cycle to the corresponding peak inspiratory and expiratory flows demanded by the wearer. It is common practice to describe the resistance imposed by aircrew breathing equipment in terms of the total change of pressure in the mask cavity [the pressure swing] and the minimum and maximum mask pressures which are produced by equal inspiratory and expiratory flows. The pressure in the mask cavity meaned over the whole of the respiratory cycle is also a valuable expression of the performance of a breathing gas system, as this quantity determines in part the cardiovascular stresses imposed by the equipment.

Total change of mask pressure

The total change (swing) of pressure in the mask cavity during the respiratory cycle (ie. the difference between the minimum and maximum mask cavity pressures) should be as low as possible. The greater the swing, the greater is the sensation of resistance to breathing and the more is the likelihood of incidents of hyperventilation, particularly in situations of high mental workload. The resistance to breathing imposed by early pressure demand oxygen delivery systems fitted to NATO aircraft was excessive, both in relation to the continuous flow systems which preceded them and the physiological standards established at the time (Chapter 2 refers). The thirty years after World War II saw a progressive reduction respiratory resistance imposed by aircrew breathing systems, particularly those developed in the United Kingdom, until by the late 1970s the resistances imposed by RAF aircrew systems were within the physiological requirements for comfortable breathing at pulmonary ventilations up to 50 L (ATPD) min^{-1} in speech and when performing the AGSM. This UK standard (Table 5.1) was adopted by the ASCC and NATO nations (2, 37) in the early 1980s as being the best compromise between physiological requirements and equipment design which can be achieved using current technology. The external respiratory work associated with these limits of mask pressure swing at pulmonary ventilations up to 30 L (ATPD) min^{-1} is two-thirds of the limit recommended by Morrison and Reimer (36) for comfortable breathing, and equals the limit recommended by Morrison and Reimer at a pulmonary ventilation of 50 L (ATPD) min^{-1}. The limits of mask pressure swing presented in Table 5.1 remain the maximum resistance acceptable for aircrew breathing equipment. Although internal airway resistance is reduced at altitude, the effect on the total work of breathing is relatively small and it is present practice to require the resistance to breathing imposed by an aircrew breathing system to be within the same maximum limits at all altitudes from ground level to 38,000 feet, above which altitude pressure breathing is operative.

Table 5.1. The Maximum Acceptable Change of Pressure in the Mask Cavity during the Respiratory Cycle at Altitudes between Ground Level and 38,000 feet

Peak Inspiratory and Expiratory Flows (litre(ATPD) min^{-1})	Maximum Change of Mask Cavity Pressure during the Respiratory Cycle (inch water gauge (kPa))	
30	2.0	(0.5)
90	3.4	(0.85)
150	7.0	(1.75)
200	12.0	(3.0)

Safety Pressure

Safety pressure is the maintenance of the pressure in the mask cavity during inspiration at a value greater than that of the environment. It is widely employed in aircrew breathing systems to prevent the flow of environmental gas into the mask when there is a failure of the seal of the mask to the face. The ingress of air, toxic fumes or nuclear, chemical or biological warfare agents through a leak between the mask and the face could have serious consequences. As long as the pressure in the mask cavity remains greater than that of the environment, then a failure of the seal of the mask to the face will result in a flow of breathing gas from the mask to the environment thus preventing the contamination of the breathing gas by air or toxic materials in the air. Although it is desirable that safety pressure is maintained in the mask cavity even at high inspiratory flows and in the presence of large leaks, the pressure-flow characteristics of most breathing gas delivery systems, in which the mask pressure falls with increasing flow, and the compensation of the expiratory valve, make this goal difficult, if not impossible, to meet (11). In such systems, a high safety pressure will be associated with a high resistance to expiration. A mean pressure in the mask cavity of +2.0 inch wg (0.5 kPa) will, however, minimise the total work of breathing (42) and increase breathing comfort.

The fraction of the inspired gas which enters a mask through a typical mask leak in a suction demand system is greatest at low inspiratory flows. The ratio of flow through the leak to total inspiratory flow falls rapidly as the latter rises (11). The presence of safety pressure is therefore most important during quiet breathing. It is thus possible to strike a compromise between the maximum inspiratory flow at which safety pressure is required to be present and the rise in mask expiratory pressures produced by the safety pressure. Present ASCC and NATO specifications (2,37) require safety pressure to be present in aircrew breathing systems at inspiratory flows of up to at least 70 L(ATPD) min^{-1} and limit the maximum mask pressures during expiration to the values presented in Table 5.2 (safety pressure present). The minimum mask pressures allowed when safety pressure is present are also presented in Table 5.2. These limits to the peak mask pressures when safety pressure is present ensure that the effects of the associated increase of intrapulmonary pressure of +1 to +2 inch wg (0.25 - 0.5 kPa) upon the circulation and distribution of body fluids are minimal and acceptable for many hours.

Table 5.2. The Minimum and Maximum Acceptable Mask Cavity Pressures during the Respiratory Cycle at Altitudes between Ground Level and 38,000 feet

Peak Inspiratory and Expiratory Flows (litre (ATPD) min^{-1})	Acceptable Mask Cavity Pressures (inch water gauge (kPa))			
	Minimum		Maximum	
A. Safety Pressure Absent				
30	-1.5	(-0.38)	+1.5	(+0.38)
90	-2.2	(-0.55)	+2.6	(+0.65)
150	-4.5	(-1.22)	+4.0	(+1.00)
200	-7.6	(-1.90)	+6.0	(+1.50)
B. Safety Pressure Present				
30	+0.1	(+0.02)	+3.0	(+0.75)
90	-0.8	(-0.20)	+3.8	(+0.95)
150	-3.5	(-0.90)	+5.0	(+1.25)
200	-7.0	(-1.75)	+6.6	(+1.65)

In some aircrew breathing systems safety pressure is only operative at altitudes above either 10,000 - 12,000 feet or 30,000 feet. Below these altitudes, gas only flows from the regulator when the pressure in the mask is reduced below that of the environment. The reduction of mask pressure which occurs during inspiration in these circumstances should not give rise to the sensation of excessive inspiratory resistance. The suction in the mask cavity is not to exceed the values specified in Table 5.2 (safety pressure absent). The maximum mask pressures which occur when safety pressure is not operative should be such that there is no sensation of excessive expiratory resistance. The maximum acceptable values are specified in Table 5.2 (Safety pressure absent).

Further Increases of Mask Pressure

In use, certain routine and emergency conditions tend to raise the pressure in the mask cavity above the values seen during breathing in the steady state. Thus, in a typical pressure demand system in which the outlet valve of the mask is compensated to the pressure in the inlet hose of the mask, head movement increases the pressure in the mask hose and hence the resistance to expiration and similarly a rise of mask hose pressure produced by a rapid ascent also increases expiratory resistance (Chapters 2 and 7 refer). In order to maintain breathing comfort, the rise of mask cavity pressure induced by realistic head movements or by the maximum rate of ascent of cabin altitude (with the cabin pressurised) is not to exceed 1.0 inch water gauge (0.25 kPa). A continuous flow failure of the demand valve in a conventional compensated mask outlet valve system will result in a continuous rise of mask pressure. If the flow through the demand valve is relatively low, the wearer will experience expiratory difficulty. A high continuous flow will produce a rapid rise of mask and intrapulmonary pressures, provided that the seal of the mask to the face is maintained. Inflation of the lungs to an intrapulmonary pressure of 80-100 mm Hg will, if the expiratory muscles are relaxed, result in over-distension of the lung parenchyma, rupture of alveoli and the passage of gas into the lung tissue, into the mediastinum, into the pleural space (pneumothorax) and most seriously into the ruptured pulmonary capillaries, producing arterial gas emboli (42). The rise of mask pressure produced by a high continuous flow failure of a demand valve must not exceed 41 mm Hg (5.5 kPa).

Venting of lungs on rapid decompression

Rapid decompression of the pressure cabin of an aircraft produces an almost equally rapid expansion of the gases in the lungs and airways and can produce over-inflation of the lungs with damage to the lung parenchyma with the consequences discussed in the previous paragraph. The incidence and severity of the damage to the lungs produced by rapid decompression are determined primarily by the ratio of cabin pressure before the decompression to that after the decompression, the speed of the decompression (the reciprocal of the time constant of the decompression), the degree of opening of the glottis and the resistance to the flow of gas from the respiratory tract imposed by the breathing equipment (32). The breathing equipment worn by aircrew should allow free venting of the expanding gases from the lungs in these circumstances. The peak transpulmonary pressure produced by a rapid decompression should not exceed the 80-100 mm Hg (10.6 - 13.3 kPag) required to produce pulmonary damage by over-inflation of the relaxed chest. Present standards for aircrew breathing equipment (2, 37) require that the mask pressure on a rapid decompression to a final altitude of 38,000 feet (above this altitude pressure breathing is operative) in 0.1 second shall not exceed 5.5 kPag [41.3 mm Hg]. This limit is somewhat arbitrary. It is one half of the intrapulmonary pressure required to damage the lungs by over-distension of the relaxed chest (42). There is recent experimental evidence that short duration (<50 msec) peak mask pressures of up to 100 mm Hg (13.3 kPag) on rapid decompression over a 5 lbf in^2 pressure change in 0.2-1.0 sec will not cause lung damage. The probability of lung damage on rapid decompression is reduced if over-distension of the lungs is prevented by the application of counter pressure to the chest wall and abdomen during the decompression.

Oscillatory activity

Aircrew breathing systems can exhibit oscillatory activity which produces oscillations of pressure in the mask, usually during inspiration. Such oscillations of mask pressure, particularly if they are of sufficient amplitude, are subjectively disturbing, may induce hyperventilation and can interfere with communication (44). The incidence, amplitude and frequency of these oscillations are determined by the oscillatory mechanics of the breathing equipment, by the impedance of the respiratory tract [when present, oscillatory activity is frequently much greater when the wearer breathes through the nose as compared with breathing through the mouth] and the respiratory flow pattern (44). Ideally any oscillatory activity which occurs should not be detectable subjectively; it must not be disturbing. Extensive studies conducted in the UK (44, 45) resulted in the requirement that the double amplitude of any oscillation of pressure in the mask cavity which persists for longer than 0.25 sec is not to exceed 0.06 kPa (0.25 inch water gauge). This standard is included in present ASCC and NATO standards (2, 37).

COMPOSITION OF THE INSPIRED GAS

Several physiological factors influence the requirements for the composition of the gas delivered to the respiratory tract. It is convenient to consider these requirements in terms of the limits to the concentration of oxygen in relation to cabin altitude. In conventional oxygen systems the diluent gas is virtually entirely nitrogen since the oxygen from the aircraft store is diluted with cabin air. The performance of molecular sieve oxygen concentrators is such that the product gas contains argon as well as oxygen and nitrogen (Chapter 6 refers). The maximum concentration of argon in the product gas is 5-6%. Laboratory studies have shown (5) that in this context argon has no specific physiological effects and can be regarded solely as an inert diluent gas.

Minimum Concentration of Oxygen in the Steady State

The principal consideration is that the concentration of oxygen in the inspired gas shall be adequate to prevent significant hypoxia. The concentration of oxygen in the inspired gas should be such that the partial pressure of oxygen (PO_2) in the alveolar gas is maintained at or above the normal value associated with breathing air at ground level ie. 103 mm Hg. A detailed review of the maximum acceptable degree of hypoxia in aircrew operating high performance combat aircraft reported elsewhere (15) led to the conclusion that the alveolar PO_2 should not be allowed to

fall below 75 mm Hg [the alveolar PO_2 produced by breathing air at an altitude of 5,000 feet] during normal flight with the cabin pressurised. The devices employed in molecular sieve oxygen concentrator systems to provide warning when the PO_2 of the product gas falls below an acceptable value have a significant tolerance band within which they may or may not provide a warning of a low PO_2. In order to ensure that adequate warning of impending hypoxia is given without spurious warnings, the minimum PO_2 of the product gas when the system is operating correctly should not be less than that required to maintain an alveolar PO_2 of 103 mm Hg. The warning system shall always provide a warning when the PO_2 of the product gas falls below that required to maintain an alveolar PO_2 of 75 mm Hg. The concentration of oxygen required to produce an alveolar PO_2 of 103 mm Hg at a given altitude is calculated using the Alveolar Gas Equation (11) with assumptions with respect to the alveolar carbon dioxide tension (PCO_2) and the respiratory exchange ratio (R). The relationship between the concentration of oxygen required in the inspired gas and altitude to produce an alveolar PO_2 of 103 mm Hg [alveolar PCO_2 = 40 mm Hg and R = 0.85] at altitudes up to 33,000 feet is presented in Figures 5.2 and 5.3.

Minimum Concentration of Oxygen to prevent Hypoxia on Rapid Decompression

A second factor which influences the relationship between the concentration of oxygen in the inspired gas and cabin altitude is the need to prevent impairment of performance due to hypoxia following a failure of the pressure cabin at high altitude (15). When the inspired gas breathed before the decompression contains a significant concentration of nitrogen, the fall of the total pressure of the alveolar gas produced by rapid decompression produces a concomitant reduction of the alveolar PO_2 which may be to such a level that it produces impairment of performance or even unconsciousness. If the decompression is to an altitude greater than 30,000 feet then 100% oxygen must be delivered to the respiratory tract immediately the decompression occurs if there is not to be a significant impairment of consciousness. There will be a significant impairment of performance if the alveolar PO_2 is reduced during the decompression to below 30 mm Hg even for only a few seconds (14). If the magnitude of the area enclosed between an alveolar PO_2 of 30 mm Hg above and the time course of alveolar PO_2 below exceeds 140 mm Hg.sec, then the individual will become unconscious (14). The decrement of performance at a choice reaction task is proportional to the magnitude of the area bordered above by a PO_2 of 30 mm Hg and the time course of the alveolar PO_2 below (14). The breathing gas delivery system shall therefore prevent the alveolar PO_2 falling below 30 mm Hg during and subsequent to a rapid decompression.

The major factors determining the minimum value of the alveolar PO_2 immediately after a rapid decompression are the initial and final absolute pressures of the alveolar gas and the composition of the gas breathed before and after the decompression. Assuming that 100% oxygen is delivered to the respiratory tract immediately the decompression occurs, the alveolar PO_2 can be prevented from falling below 30 mm Hg by ensuring that the gas breathed before the decompression contains an adequate concentration of oxygen and that the total intrapulmonary pressure does not fall below 115-120 mm Hg absolute.

The concentrations of oxygen required in the inspired gas to produce an alveolar PO_2 of 30 mm Hg immediately after a rapid decompression from a given initial cabin altitude to a given final cabin altitude [total absolute alveolar gas pressure at final cabin altitudes above 40,000 feet] are indicted by the interrupted curves of Figure 5.2. The relationship between initial cabin altitude and the final cabin altitude is determined by the pressurisation schedule of the cabin of the aircraft. The final alveolar gas pressure is also determined by the safety pressure/pressure breathing characteristics of the breathing gas delivery system. Thus the curve relating the minimum concentration of oxygen in the inspired gas to cabin altitude before a decompression required to prevent the alveolar PO_2 falling below 30 mm Hg immediately after the decompression will depend upon the cabin pressurisation schedule of the aircraft and the safety pressure/pressure breathing characteristics of the breathing gas delivery system.

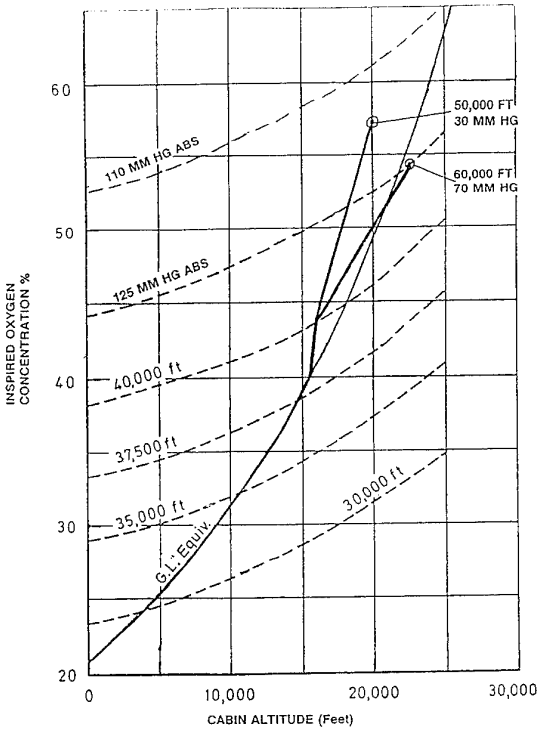

Fig. 5.2. The relationships between the concentration of oxygen in the inspired gas and cabin altitude required (i) to maintain an alveolar $P0_2$ of 103 mm Hg (GL equivalent); (ii) to produce an alveolar $P0_2$ of 30 mm Hg on rapid decompression to various final altitudes and intrapulmonary pressures (broken lines); and (iii) to ensure rapid decompression of a 5 Lb in^{-2} pressure cabin will produce a minimum alveolar $P0_2$ of 30 mm Hg when using two common pressure breathing schedules above 40,000 feet (solid curves).

The minimum inspired oxygen concentration-cabin altitude curves for two commonly used pressure breathing systems employed in aircraft with a cabin pressure differential of 5 Lb in^{-2} at aircraft altitudes above 23,000 feet are presented in Figure 5.2. Both of these pressure breathing systems commence pressure breathing at a cabin altitude of 40,000 feet and deliver oxygen at an absolute pressure which falls linearly with the reduction of environmental pressure at altitudes above 40,000 feet. One system employs a breathing pressure of 30 mm Hg at 50,000 feet which provides an

intrapulmonary pressure of 117.5 mm Hg absolute at 50,000 feet. The other system employs a breathing pressure of 70 mm Hg at 60,000 feet which provides an intrapulmonary pressure of 124 mm Hg absolute at 60,000 feet. It may be seen from Figure 5.2 that the minimum concentration of oxygen required in the inspired gas to prevent significant hypoxia being induced by the rapid decompression is greater than that required to maintain an alveolar PO_2 of 103 mm Hg in the steady state at cabin altitudes above 16,000 feet. The concentration of oxygen required in the inspired gas at cabin altitudes above 16,000 feet is greater with the pressure breathing system which employs a breathing pressure of 30 mm Hg at 50,000 feet than the system which employs a breathing pressure of 70 mm Hg at 60,000 feet. The minimum concentration of oxygen required in relation to cabin altitude to prevent hypoxia in the steady state and in the event of a rapid decompression in an aircraft with a 5.0 Lb in^{-2} differential pressure cabin and using a breathing pressure of 30 mm Hg at 50,000 feet is summarised in Figure 5.3.

Maximum Concentration of Oxygen

Breathing high concentrations of oxygen during flight in high performance, combat aircraft has two important disadvantages. It results in acceleration atelectasis and delayed otitic barotrauma.

Exposure to sustained positive acceleration whilst breathing high concentrations of oxygen produces marked collapse of the lower part of the lungs due to the absorption of alveolar gas whilst the medium sized airways are collapsed by the increased weight of the lungs (17). The symptoms of the condition are attacks of coughing accompanied often by a sense of difficulty of breathing or, less frequently, by discomfort in the chest. The coughing is usually provoked by an attempt to take a deep breath either in flight or, more frequently, on standing up in the cockpit after flight. The cough and difficulty in breathing may last a few moments or repeated attacks may occur over a period of 10 to 15 min. Field studies (10, 21) have shown that 80-85% of pilots develop the condition with symptoms in flights in which 100% oxygen is breathed and manoeuvres above 3-4G are performed. The lung collapse which often reduces the vital capacity by 50% is associated with a large right to left shunt (20-25% of the cardiac output) of venous blood flowing through the collapsed lung (20). The collapse remains after the return to +1 G_z until the individual takes a deep breath and/or coughs.

Extensive laboratory studies using man carrying centrifuges (16, 20, 27, 25) have confirmed that the causative factors of acceleration atelectasis are exposure to $+G_z$ accelerations greater than 3-4G and breathing 100% oxygen, and that the degree of lung collapse and the intensity of the symptoms are greatly increased by inflation of the G trousers. The mechanism is absorption of gas from non-ventilated alveoli in the lower parts of the lungs. The ventilation of these alveoli ceases on exposure to $+G_z$ acceleration as the increased weight of the lung above compresses the lower parts of the lung, closing the small and intermediate sized airways. Inflation of the abdominal bladder of the G trousers accentuates this process. A high concentration of nitrogen in the non-ventilated alveoli will maintain the patency of the latter whilst the increased accelerative force is operative and ventilation of the alveoli will recommence on return to 1G. If, however, the gas breathed before the exposure to $+G_z$ acceleration is 100% oxygen so that the concentration of nitrogen in the alveoli is very low, the blood flowing through the non-ventilated alveoli rapidly absorbs all the gas trapped in the alveoli and surface forces maintain the alveoli in the collapsed state after the return to 1G until they are reopened by a deep inspiration and coughing. The rate of absorption of gas from non-ventilated alveoli is increased sixty times when 100% oxygen is breathed instead of air before the cessation of ventilation of the lungs (41). The presence of a significant concentration of nitrogen which has a much lower solubility in blood than oxygen and carbon dioxide acts as a brake on the absorption of gas from the non-ventilated alveoli. Mixed venous blood continues to flow through the collapsed lungs and thus the condition produces a right to left shunt, the magnitude of which varies with the degree of acceleration atelectasis. Whilst such a shunt may be of little significance with respect to the oxygen content of the arterial blood for as long as 100% oxygen is breathed at low altitude, it would produce a very significant decrease in the arterial oxygen saturation if the alveolar PO_2 was reduced to below 100 mm Hg by a subsequent exposure to high altitude.

Although no long term deleterious effects have been found in aircrew who have had the condition repeatedly in flight, many air forces consider that the chest discomfort which is produced and the potential hazard to safety of coughing in flight make acceleration atelectasis unacceptable. Extensive flight and laboratory trials conducted by the Royal Air Force in the early 1960s (16, 20) and repeated by the United States Air Force (25) demonstrated clearly that acceleration atelectasis does not occur if the concentration of nitrogen in the gas breathed before and during the exposure to the sustained acceleration does not fall below 40%. In this context, the argon which is present in breathing gas produced by molecular sieve oxygen concentrators behaves as nitrogen (25) as it is also relatively insoluble in blood. Laboratory studies suggest that the concentration of nitrogen required to prevent significant acceleration atelectasis at altitudes up to 25,000 feet is also 40% (12). Flight experience at cabin altitudes up to 20,000 feet confirms this finding.

The Royal Air Force has required since 1960 that the concentration of oxygen delivered by aircraft oxygen systems when in the air dilution mode does not exceed 60% at cabin altitudes below 20,000 feet. In practice the need for economy in the use of oxygen in high performance combat aircraft has led to the use of air dilution demand regulators in most NATO air forces. The maximum concentration of oxygen delivered by these regulators in the air dilution mode at cabin altitudes up to 20,000 feet has been less than 60% and acceleration atelectasis has not occurred. The United States Navy has employed 100% oxygen in many of its combat aircraft over this period in order to enhance protection against toxic fumes in the cabin and against drowning on parachuting into the sea. US Navy aircrew have reported the symptoms of acceleration atelectasis in flight.

Breathing 100% oxygen, especially if it is associated with even moderate ascent to and descent from altitude, is followed in the vast majority of individuals by the development of ear discomfort and deafness (delayed otitic barotrauma). A typical picture is that, on waking from a night's sleep, following flights in which 100% oxygen has been breathed, the individual has discomfort in the ears and is moderately deaf. Examination of the ear shows that the ear drum is drawn into the middle ear and that there is fluid in

the middle ear. The discomfort and deafness can be corrected by performing Frenzel's manoeuvre – which introduces air into the middle ear. The mechanism underlying the ear discomfort and deafness is similar to that which produces the lung collapse on exposure to $+G_z$. Breathing 100% oxygen results in the nitrogen normally present in the middle ear cavity being washed out and replaced by oxygen through the pharyngo-tympanic tube. In the absence of nitrogen or the presence of a low concentration of oxygen in the middle ear cavity the blood flowing through the wall of the cavity rapidly absorbs gas from the cavity (28). The absorption of gas reduces the pressure in the middle ear which draws the ear drum into the cavity causing discomfort and deafness. The reduction in pressure also draws fluid into the cavity. The process of absorption of gas from the middle ear can be slowed and arrested after flight by "clearing the ears" whilst breathing air. The re-introduction of nitrogen into the middle ear must be repeated several times over the 12-18 hours following a flight in which 100% oxygen is breathed if delayed otitic barotrauma is to be avoided. However, if several ascents to altitude (even to only 5,000 feet) have been performed whilst breathing 100% oxygen the absence of ventilation of the middle ear which occurs during sleep results in ear discomfort and deafness the following morning.

The incidence of delayed otitic barotrauma is reduced by the presence of a minimum concentration of nitrogen in the gas breathed during flight. The concentration of nitrogen required in the inspired gas to reduce the incidence and severity of this condition to negligible levels is between 40% and 50%. Laboratory evidence suggests that the incidence of delayed otitic barotrauma will be very low when the nitrogen concentration is between 30% and 40%.

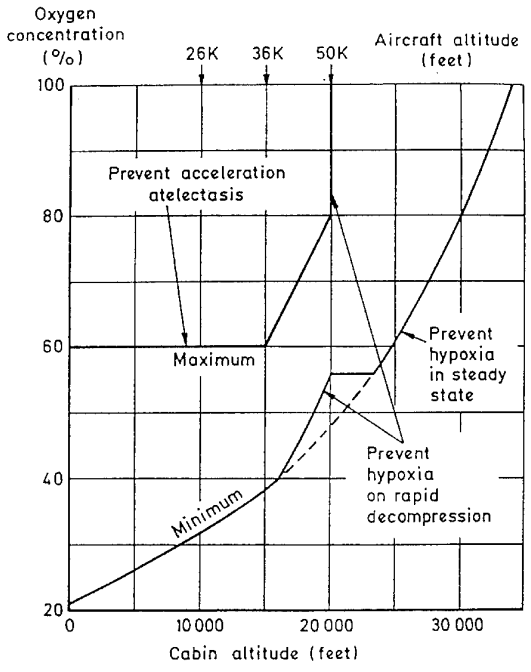

Fig. 5.3. A specification of the requirements for the relationships of the concentration of oxygen in the inspired gas and cabin altitude in the intact pressure cabin of a typical agile combat aircaraft with a ceiling of 50,000 feet.

Thus the requirements to avoid acceleration atelectasis and delayed otitic barotrauma in flight set the limit to the maximum concentration of oxygen which should be present in the gas delivered to the respiratory tract by the breathing system of a high performance combat aircraft. It has been seen that this requirement can be met by limiting the maximum oxygen concentration to 60%. There are obvious limits to the maximum altitude up to which this requirement can be applied. Three factors play a part in deciding the range of cabin altitudes over which it should be applied. The first factor is cabin pressurisation schedule. Aircrew operating combat aircraft will only be exposed to cabin altitudes greater than 20,000-22,000 feet in the rare event of decompression of the cabin at high altitude when 100% oxygen must be breathed in order to prevent hypoxia. The second factor is the effect of high altitude upon the ability of the aircraft to sustain significant levels of acceleration. The performance and operational roles of many current high performance combat aircraft is such that the aircrew are very unlikely to be exposed to sustained $+G_z$ accelerations at aircraft altitudes above 36,000 feet i.e. at cabin altitudes above 15,000 feet. Future agile combat aircraft may, however, be capable of exposing aircrew to significant levels of $+G_z$ acceleration at aircraft altitudes greater than 35,000 - 40,000 feet. The third factor which is relevant is that the design of the breathing system become more technically difficult and costs rise if the difference between the minimum and maximum allowable oxygen concentrations is very small. Such would be the case if the specification of performance required that the concentration of oxygen should not exceed 60% at cabin altitudes much above 15,000 feet. Taking all these factors into consideration, the present compromise is that the concentration of oxygen in the inspired gas delivered by the breathing system of a high performance combat aircraft should not exceed 60% at cabin altitudes up to 15,000 feet (Figure 5.3).

Although the symptoms of decompression sickness occur very rarely in current combat aircraft operations, the possibility of extended duration flights at cabin altitudes above 15,000-18,000 feet has led to the suggestion that pilots of combat aircraft should breathe 100% oxygen throughout flight in order to reduce the hazard of serious decompression sickness arising either during high altitude flight or after decompression of the pressure cabin at high altitude (48). Whilst there is no doubt that breathing 100% oxygen throughout flight would reduce the probability of decompression sickness occurring at high cabin altitudes or following rapid decompression of the cabin at high altitude, breathing 100% oxygen produces lung collapse on exposure to $+G_z$ accelerations and delayed otitic barotrauma. Furthermore, the incidence of significant symptoms of decompression sickness at cabin altitudes up to 20,000 feet in combat aircraft is extremely low. Present evidence also suggests that if immediate descent is undertaken to altitudes below 25,000 feet following decompression of the cabin, serious decompression sickness will only occur rarely, even if the gas breathed prior to the decompression contains 45-50% nitrogen. Indeed, this assumption is one of the bases of many "get-me-down" partial pressure suit systems (13). The balance between the requirement to avoid the disadvantages of breathing 100% oxygen throughout flight and the possibility of developing significant decompression sickness either with the cabin pressurised or following loss of cabin pressure, varies with the cabin pressurisation schedule of the aircraft and the flight profiles to be employed operationally.

Whilst conventional oxygen systems which employ gaseous or liquid oxygen stores in the aircraft can provide 100% oxygen throughout flight (this procedure may however limit the duration of a sortie), several of the molecular sieve oxygen concentrator systems now in service or to be fitted to combat aircraft to be introduced into service towards the end of the 1990s, will not provide the completely nitrogen-free breathing gas in flight which is required to eliminate decompression sickness.

The balance struck at present by many air forces is to require that the concentration of oxygen in the breathing gas does not exceed 60% at cabin altitudes up to at least 15,000 feet, and to require that 100% oxygen is delivered to the respiratory tract immediately a failure of the pressure cabin exposes the crew to a cabin altitude in excess of 22,000 to 25,000 feet. The limits to the acceptable concentrations of oxygen in the inspired gas during flight with the cabin pressurised in a typical agile combat aircraft with an operational ceiling of 50,000 feet are presented in Figure 5.3.

PRESSURE BREATHING AT ALTITUDE

The principal physiological hazards associated with loss of cabin pressure at altitudes above 40,000 feet are hypoxia, decompression sickness and cold injury. A full pressure suit assembly is necessary if protection against all three hazards is required over a prolonged period (13). However if the aircraft can descend promptly and rapidly (within 3-4 minutes) to an altitude of less than 40,000 feet, protection against hypoxia only is required. A full pressure suit assembly will provide the ideal physiological protection but it is bulky, cumbersome, impairs operational efficiency during routine flying with an intact cabin, and imposes major ground procedural problems. Most air forces have therefore adopted pressure breathing combined with partial pressure garments at altitudes in excess of 50,000 feet to provide short term or "get-me-down" protection against hypoxia. Partial pressure garments are required to combat the undesirable physiological disturbances produced by pressure breathing but in order to exploit the advantages of the partial pressure approach (less restriction when uninflated and inflated, greater routine comfort and lower thermal load), it is desirable that counterpressure should be applied to the minimum surface of the body. Thus the design of the counterpressure garments represents a compromise between ideal physiological requirements and functional convenience. In addition, since the protection against hypoxia using a partial pressure assembly is required for only a short period of time during emergency descent, some compromise in the level of alveolar partial pressure of oxygen which is required is also acceptable. It is the interaction of the deleterious effects of hypoxia upon mental performance and the cardiovascular system, with the undesirable consequences of positive pressure breathing, which determine the acceptable minimum alveolar PO_2. Virtually all pressure breathing systems and partial pressure assemblies employ 100% oxygen in order to minimise the magnitude of the breathing pressure required at altitudes above 40,000 feet to maintain the required alveolar PO_2. There have been limited studies of the use of product gas from a molecular sieve oxygen concentrator comprising 5-6% argon and 94-95% oxygen during pressure breathing at an altitude of 50,000 feet (38), which confirmed the need to raise the breathing pressure to maintain the inspired PO_2 at the appropriate level.

Pressure breathing with a pressure sealing mask and no counterpressure to the body is widely used to provide short duration protection against hypoxia on exposure to altitudes up to 48,000-50,000 feet. The mean mask cavity pressure required at 50,000 feet is a compromise between too high a pressure which will produce syncope, and too low a pressure which will not prevent a serious deterioration of performance due to hypoxia (13). The acceptable compromise is a mean mask pressure between 16-18 inch water gauge (4.0 and 4.5kPa) at 50,000 feet. Between 38,000 feet and 50,000 feet the mean mask pressure should increase linearly with fall of environmental pressure, the limits of mean mask pressure at 40,000 feet being 0.4 to 4.0 inch water gauge (+0.1 to 1.0 kPa). During pressure breathing with a mask alone the total change of mask cavity pressure during the respiratory cycle should not exceed 2.0 inch water gauge (0.5 kpa) at peak inspiratory and expiratory flows of 30 L(ATPD) min^{-1} and 4.0 inch water gauge (1.0 kPa) at peak inspiratory and expiratory flows of 110 L (ATPD) min^{-1}.

The magnitude of the breathing pressure required to prevent unacceptable hypoxia at altitudes above 50,000 feet requires the application of counterpressure to the chest and abdomen to support breathing and at higher altitudes counterpressure to at least a portion of the limbs to counteract the effects of the raised intrapulmonary pressure upon the cardiovascular system, and maintain an adequate systemic arterial pressure and blood flow to the brain (13). Thus all partial pressure assemblies apply counterpressure to the external surface of the chest, most commonly by means of a bladder covering part or all of the chest and restrained within an outer inextensible fabric layer. The bladder is connected into the hose between the breathing gas demand regulator and the oronasal mask/pressure helmet so that it is inflated with breathing gas to the breathing pressure provided by the regulator. The bladder of the pressure jerkin employed in the partial pressure assemblies introduced into the Royal Air Force in the late 1950s (13) not only applies counterpressure to the chest but also to the whole of the abdomen which ensures the minimum of respiratory disturbances during pressure breathing. In more recent partial pressure assemblies counterpressure is applied to the abdomen and lower limbs by means of the G-trousers which the crew member is primarily wearing to enhance tolerance of $+G_z$ acceleration. Following experimental work conducted in UK (13), Sweden (31) and Canada (1), the pressure in the G trousers during pressure breathing at altitude has been raised above the breathing pressure by a factor of 1.5 to 3.2 times the breathing pressure. The optimum ratio of G trouser to breathing pressures varies with the degree of coverage provided by the G trousers and is about 2.0 when using the UK full coverage anti G trousers (19).

The excellent sealing properties of the RAF type P/Q oronsasl masks developed in the mid 1950s introduced the possibility of replacing cumbersome partial pressure helmets by an oronasal mask in short duration partial pressure assemblies. Extensive studies of the limitations to the delivery of high breathing pressures to the respiratory tract by means of an oronasal mask (13) demonstrated that a well sealing oronasal mask could be used to deliver breathing pressures of up to 70 mm Hg (9.3 kPag) for several minutes. A limited proportion of subjects can even tolerate pressure breathing with the type P/Q mask at pressures up to 80 mm Hg (10.7 kPag). The practical limit to the use of an oronasal

mask without external support to the upper neck is probably a breathing pressure of 70 - 75 mm Hg (9.3 - 10.0 kPag).

Partial pressure assemblies which employ a partial pressure helmet to deliver 100% oxygen to the respiratory tract maintain the absolute intrapulmonary pressure at 140 - 150 mm Hg at all altitudes above 40,000 feet which, in the absence of hyperventilation, gives an alveolar PO_2 of 50 - 60 mm Hg. The use of a breathing pressure of only 30 mm Hg at 50,000 feet results in an intrapulmonary pressure of 117 mm Hg absolute and an alveolar PO_2 of 40 mm Hg with a moderate degree of hyperventilation (alveolar PCO_2 = 30 mm Hg). This degree of hypoxia rapidly results in moderate to severe impairment of performance (13). The requirement to raise the altitude at which an oronasal mask could be used with counterpressure to the trunk and lower limbs as high as possible resulted in an extensive study of the degree of hypoxia which is acceptable during short duration pressure breathing at breathing pressures up to 70 mm Hg. These studies (13) demonstrated that an intrapulmonary pressure of 130 mm Hg absolute produced only mild impairment of mental and motor performance, whilst an intrapulmonary pressure of 120 mm Hg absolute led to mild to moderate impairment. Several current partial pressure assemblies comprising an oronasal mask with counterpressure to the trunk and lower limbs employ a breathing pressure of 70 mm Hg (9.3 kPag) at an altitude of 60,000 feet which provides an intrapulmonary pressure of 124 mm Hg absolute and an alveolar PO_2 of 45-50 mm Hg. The relationship of breathing pressure (mask pressure) to altitude between 40,000 and 60,000 feet can take several forms (Figure 5.4).

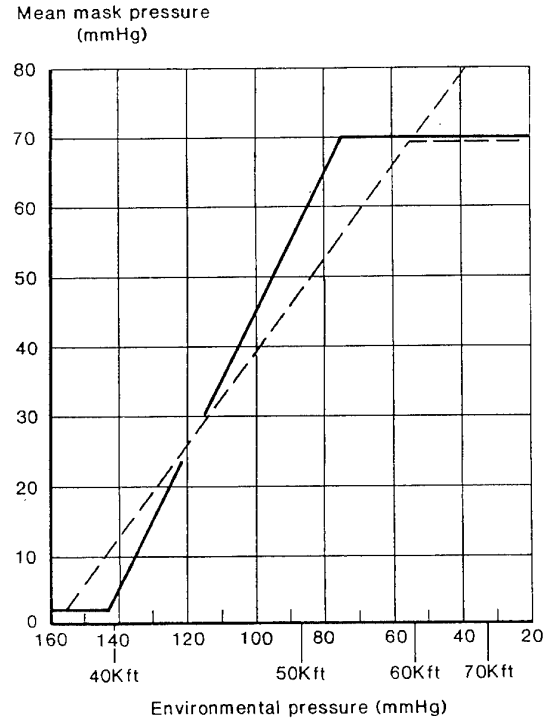

Fig. 5.4. Two acceptable forms of the relationship between mean mask pressure and altitude for a partial pressure assembly comprising a mask, pressure waistcoat and G trousers.

The mask pressure can be held at 141 mm Hg absolute with ascent above 40,000 feet until the breathing pressure reaches the maximum of 70 mm Hg [Figure 5.4 - solid line]. This relationship minimises the hypoxia at the intermediate altitudes. An alternative relationship is one in which the absolute pressure in the mask falls linearly with environmental pressure from 40,000 to 60,000 feet [Figure 5.4 - broken line]. This form of the relationship minimises the cardiovascular stress at the intermediate altitudes. The mask pressure meaned over the respiratory cycle during pressure breathing at altitudes above 50,000 feet is to be within 2 mm Hg (0.27 kPa) of the nominal mask pressure.

The resistance to breathing during pressure breathing with respiratory counterpressure is determined by the relationships of the pressures in the mask cavity, the pressure applied to the chest by the respiratory counterpressure garment [which is generally assumed to be the pressure in the bladder, if a bladder system is used] and the pressure applied to the abdomen by the G trousers. The swings of pressure in the mask cavity and the chest counterpressure garment during pressure breathing with counterpressure should not exceed the limits specified in Table 5.1. The difference between the pressure in the mask cavity and the chest countepressure garment shall at no time exceed 2.0 inch wg (0.5 kPa).

The required intrapulmonary pressure must be established rapidly on a sudden decompression to high altitude if hypoxia is to be avoided. A suitable standard is that on a rapid decompression (in 0.1 sec) to an altitude above 45,000 feet the pressures in the mask cavity and in the respiratory counterpressure garment shall not fall below 120 mm Hg (16 kPa) absolute for longer than 2 sec. This standard can determine the requirement for the rate of inflation of the respiratory counterpressure garment. In practice, however, where the garment will usually be inflated to safety pressure prior to a decompression, there is a need to vent excess gas from the garment to avoid over-pressurisation, although the latter can provide some protection against lung damage on a very rapid decompression.

PRESSURE BREATHING FOR $+G_z$ PROTECTION

Pressure breathing with chest counterpressure and G trouser inflation is now a well established technique for raising the tolerance of $+G_z$ accelerations (43,39,40). Pressure breathing with chest counterpressure together with extended cover G trousers such as the RAF Full Coverage Anti G Trousers or the USAF Advanced Technology Anti Suit will maintain full consciousness and vision in seated relaxed subjects during prolonged exposures to +8 to $+9G_z$. As with pressure breathing at altitude assemblies, the bladder of the chest counterpressure garment is connected into the breathing gas hose between the pressure demand regulator and the oronasal mask. The pressure demand regulator provides pressure breathing in response to the rise in the pressure at the outlet of the anti G valve. The latter typically controls the flow of cooled engine bleed air into and out of the G trousers. The anti G valve inflates the G trousers rapidly (within 1-2 sec) to the desired pressure in relation to the total applied $+G_z$. The relationship between pressure in the G trousers and applied G is virtually identical to that which has been employed in conventional G trouser systems over the last 40 years - inflation commencing at +2G and G trouser pressure rising linearly with acceleration to 10.5 Lb $in^{-2}g$ [72 kPag] at 9G.

Several series of studies on man carrying centrifuges (43, 39) and in flight (40) have demonstrated that the optimum

breathing pressure at 9G is 60-65 mm Hg (8.0 - 8.7 kPag). Various relationships between pressure breathing and acceleration have been explored (39). The preferred relationship is to commence pressure breathing at 4 G and for the breathing pressure to rise linearly to 60-65 mm Hg (8.0-8.7 kPag) at 9G. There may be an advantage in delaying the onset of pressure breathing to a higher level of acceleration in order to minimise the incidence and severity of arm pain in cockpits where the hands are placed below heart level (39).

The resistance to breathing during pressure breathing with G should be minimal. The total swing of mask pressure should not exceed the limits specified in Table 5.1. The difference between the pressures in the chest counterpressure garment and the mask cavity should not exceed 2.0 inch wg (0.5 kPa). Pressure breathing must not be operative unless the G trousers are pressurised as pressure breathing on exposure to $+G_z$ acceleration without pressurisation of the G trousers will rapidly cause loss of consciousness. The inflation of the chest counterpressure garment and the rise of pressure in the mask and garment on the sudden application of $+G_z$ must not lag more than 0.5 sec behind the rise of pressure in the G trousers. The chest counterpressure garment should also deflate rapidly on cessation of exposure to $+G_z$ acceleration. The fall of pressure in the mask and chest garment should not lag more than 0.5 sec behind the fall of pressure in the G trousers.

PRESSURE BREATHING - PRESS-TO-TEST

A facility whereby pressure breathing may be obtained by the operation of a manual control is required to enable the user to test the standard of seal of the low pressure delivery system up to and including the mask. The performance of this facility is to be such that the user can perform several respiratory cycles with the mask pressure raised.

The test pressure to be employed varies with the pressure breathing assembly in use. The mean mask pressure produced on press-to-test when a mask is worn alone should be within the limits +26 to +34 mm Hg (+3.5 to +4.5 kPag). When chest counterpressure and G trousers are worn the facility should provide a mask pressure of +50 to +60 mm Hg (6.7 to 8 kPag) and inflation of the G trousers to 1-2 times breathing pressure. This mask pressure is also to be provided in a press-to-test facility for a pressure breathing with G assembly. It should be noted that it is not acceptable to provide this facility simply by inflating the G trousers to the appropriate pressure (9 - 10.5 Lb $in^{-2}g$ (62 - 72 kPag)) as the application of these G trouser pressures at $+1G_z$ gives rise to severe pain. The total change of mask cavity pressure during the operation of the press-to-test facility should not exceed 3.0 inch wg (0.75 kPa) at peak respiratory flows of 30 (ATPD) min^{-1}.

PROTECTION AGAINST HYPOXIA AFTER EJECTION

The delivery of breathing gas to the respiratory tract following ejection from an aircraft at altitude shall be such that significant hypoxia does not occur during the subsequent descent of the crew member to below 10,000 feet. Typical descent times from various altitudes to 10,000 feet (29) are presented in Table 5.3.

Table 5.3 Time to descend to 10,000 feet following ejection

Starting Altitude (feet)	Time to descent to 10,000 feet (sec)	
	Man alone	Man in ejection seat*
20,000	40-60	70
30,000	70-110	130
40,000	95-160	130
50,000	110-190	215
60,000	130-220	245

* Ejection seat with 64 inch (1.62 m) diameter drogue

The time taken to descend from altitudes up to 20,000 - 25,000 feet is such that breathing air throughout the whole of the descent will not cause significant impairment of performance. Thus it is not essential to provide supplemental oxygen for escape at altitudes up to 25,000 feet. Breathing gas with a PO_2 greater than 130 - 160 mm Hg is required to prevent hypoxia on escape at altitudes above 25,000 feet. Pressure breathing is required at altitudes above 40,000 feet. Inward relief whereby the ejectee/parachutist can breathe ambient air in the event of either cessation of the breathing gas supply or separation from the ejection seat, is required. The headgear including the mask and its supply system must remain intact and remain in place during ejection and perform satisfactorily thereafter. The breathing equipment must perform satisfactorily at low temperature (-40°C to -60°C) in the presence of representative air movement [at least 20 knots (37 $km.h^{-1}$)].

PROVISION OF INWARD RELIEF

The ability to breathe air is required in the event that the flow of breathing gas provided by the breathing equipment is inadequate to meet the inspiratory demand. This facility is necessary in order to avoid a sudden failure of the supply of breathing gas imposing a very high resistance to inspiration, a situation which could threaten flight safety. The inward relief facility must not allow ambient air to dilute the breathing gas delivered by the breathing system during normal operation of the equipment and thereby cause hypoxia or to allow toxic material in the air to enter the breathing system. The crew member should be aware immediately that air is entering the breathing system. In many conventional breathing systems inward relief is obtained either by loosening the mask so that air can be inspired around it or by disconnecting the inlet hose of the mask from the supply system. Neither of these methods is satisfactory. Some systems employ a spring loaded inward relief valve in the wall of the mask or mask hose connector. The minimum suction required to open such an inward relief valve should be 5-7 inch wg (1.25 - 1.75 kPag) in order to ensure that the opening of the valve is noticed immediately by the wearer but that the inspiratory resistance is acceptable for breathing up to at least 30 minutes and will not depress the respiration of an unconscious crew member (33).

CONCLUSIONS

The physiological requirements for the advanced breathing systems to be fitted to agile high performance combat aircraft are based in general upon the performance of the best of the conventional pressure demand oxygen systems at present in use in NATO aircraft. Thus the external resistance to breathing imposed by advanced breathing systems should be within the limits specified in the present ASCC and NATO standards (2, 37) with perhaps an extension to peak respiratory flows of 250 L (ATPD) min^{-1}. The breathing system must prevent excessive rises of mask pressure during normal operation and in the event of a failure of the breathing equipment or the pressure cabin. The concentration of oxygen in the breathing gas delivered to the respiratory tract should be within the limits required to prevent hypoxia during routine flight and on decompression of the cabin at high altitude and to avoid acceleration atelectasis and delayed otitic barotrauma as already required by present ASCC and NATO standards (2, 37). It may be appropriate to consider the provision of nitrogen free breathing gas to provide protection against decompression sickness if the operational role of future combat aircraft involves prolonged operations at very high altitudes (at aircraft altitudes much above 60,000 feet). Adequate "get-me-down" protection against hypoxia can be provided in such aircraft at altitudes up to at least 60,000 feet using partial pressure assemblies employing an oronasal mask, a chest counterpressure garment and G trousers, and proven breathing pressure-altitude schedules. The breathing gas system should, in highly agile combat aircraft provide, using the same personal equipment, pressure breathing to enhance tolerance of high sustained $+G_z$ accelerations. Whilst the level of pressure breathing required at $8\text{-}9G_z$ is well established, the level of pressure breathing required at lower levels of $+G_z$ acceleration is a topic of current research.

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Chapter 6

MOLECULAR SIEVES, PRESSURE SWING ADSORPTION, AND OXYGEN CONCENTRATORS

Kenneth G. Ikels and George W. Miller

INTRODUCTION

As described in Chapter 3, the development of onboard oxygen generation systems has undergone several transformations, but at the present time, has centered on pressure swing adsorption (PSA) using molecular sieves. While other oxygen generation techniques have been flight tested, the only OBOGS technology currently flying in production aircraft is based on molecular sieves and PSA. This is due to MSOGS simplicity, lower energy consumption, reduced maintenance costs, and long life, when compared to other OBOG systems. Use of MSOG technology in military aircraft eliminates the logistics tail associated with liquid oxygen, improves safety, reduces aircraft turnaround time, and extends mission duration (which can be limited by oxygen storage capacity), and significantly lowers operational costs. This chapter reviews the chemical and physical basis for molecular sieve separation of air using pressure swing adsorption, and describes the important factors in the design of molecular sieve oxygen concentrators.

THE ADSORPTION PROCESS

Physical Adsorption

When a gas is exposed to a solid surface, the gas molecules will bind or attach to the surface due to forces occurring at the gas-solid interface. This phenomena is known as adsorption, and may be categorized as either chemisorption or physical adsorption. Chemisorption involves electron transfer between the gas and solid which results in the formation of a chemical bond. Chemisorption is generally considered to be an irreversible process. In physical adsorption, molecules are held to the solid surface by relatively weak electrostatic or van der Waals forces which do not involve the transfer of electrons. Hence, physical adsorption is reversible. Only physical adsorption is employed in gas separation processes. Adsorption of a gas on a solid is a spontaneous process accompanied by a decrease in the free energy of the system with attendant evolution of heat, i.e., the process is exothermic. Physical adsorption is characterized by relatively low heat release, generally two or three times the latent heat of evaporation, and by the fact that an adsorption equilibrium is established rapidly. Chemisorption, on the other hand, is accompanied by much higher heats of adsorption, which result from the formation of new chemical compounds.

In general, the amount of gas adsorbed by a solid depends on the type of adsorbent, the composition of the gas, and the temperature and pressure. The relationship between the amount of gas adsorbed and the pressure at constant temperature is called an adsorption isotherm. Figure 6.1 illustrates adsorption isotherms for pure nitrogen, oxygen and argon on molecular sieve type 13X at 24 °C (9, 11). Molecular sieve 13X adsorbs more than twice the amount of nitrogen as oxygen or argon up to a pressure of about four bar (4 atm). Nitrogen is preferentially adsorbed due to the favorable interaction between the molecular sieve's electrostatic fields and the weak polarity of the nitrogen molecule. The higher capacity for nitrogen, compared to oxygen and argon, forms the basis for the molecular sieve air separation process.

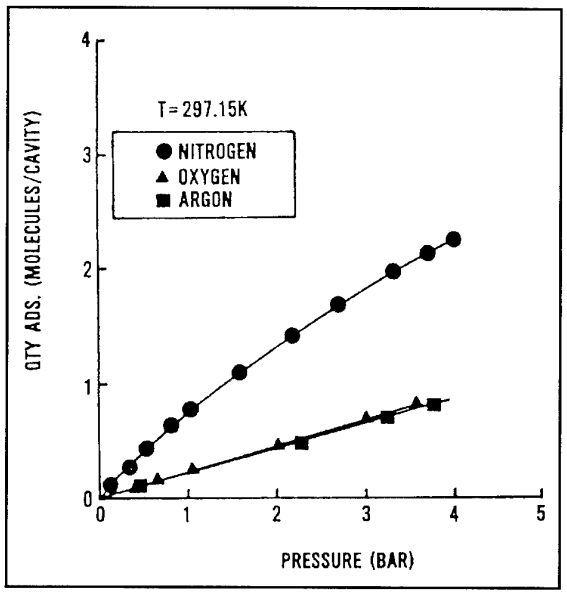

Fig. 6.1 Adsorption isotherms for pure Nitrogen, Oxygen and Argon on molecular sieve type 13X at 297.15°K (24 °C). Data from Miller (9,11).

Adsorbents

Adsorbents used commercially for the separation of mixtures of gases include the traditional microporous adsorbents such as activated carbons, clays, alumina, and silica gel, as well as the more recently developed crystalline aluminosilicates or molecular sieves. While all these materials exhibit a highly porous structure and have a large surface area available for adsorption, they differ fundamentally with respect to the range of pore size. In the traditional adsorbents there is a distribution of pore diameters which may be narrow (20 to 50 Angstrom) as in a high grade silica gel, or may range from 20 to several thousand Angstrom as in some activated carbons. By contrast, the micropore size of molecular sieves is controlled by the crystal structure and the pore size is highly uniform throughout the material. For example, the pore opening for 13X molecular sieve is fixed at 7.4 Angstrom by the chemical composition and manufacturing process. The molecular sieves, by virtue of this characteristic, have unique adsorptive properties which make them highly suited for air separation (5).

Molecular Sieves

Molecular sieves adsorbents belong to a class of compounds known as zeolites. Zeolites are hydrated crystalline metal alumino-silicates, made up of Group I and Group II elements, particularly sodium, potassium, and calcium. The structural formula for a crystal unit cell is

$$Mx/n[(AlO_2)x(SiO_2)y].wH_2O$$

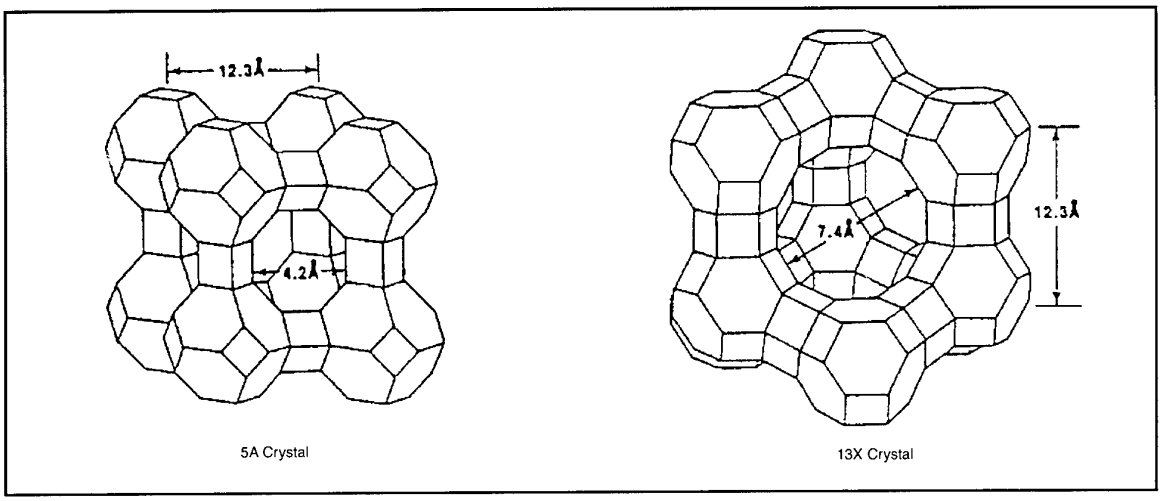

Fig. 6.2 Crystalline structure of Type 5A and 13X molecular sieves.

where M is the alkali metal cation of valence n, w is the number of water molecules and y/x is the silica to alumina ratio which usually lies between one and five. The most important property of zeolites is their internal porosity which derives from their dehydrated crystalline structure. With very active zeolites, the external surface area constitutes less than one percent of the total area available for adsorption. These materials have a great deal of internal volume available for adsorption which is only accessible by a network of channels or apertures (Figure 6.2). Molecules small enough to enter the channels can access the internal volume where the crystal adsorption sites are located.

The first definitive experiments to show that naturally occurring zeolite minerals could be used to separate gas mixtures were conducted by Barrer in 1945 (2). Highly active and selective zeolites occur only rarely in nature. The invention of synthetic zeolites or molecular sieves in 1954 by Milton (19) was a major technological breakthrough which led to the practical application of these materials in commercial separation processes. Synthetic molecular sieves are produced by a hydrothermal process which yields a very high internal volume and dimensionally uniform pores. The crystalline molecular sieves are precipitated from alkaline solution as a fine powder in the size range from 1 to 5 microns. The powder is then bonded with a clay binder and formed into granules, spheres, or extruded as pellets. The clay binder generally makes up about 20% of the commercial molecular sieve material used in air separation.

Molecular sieves act primarily as physical adsorbents; that is, adsorbed molecules are held within the crystalline structure by relatively weak intermolecular forces. Molecular sieves are high-capacity selective adsorbents that separate gaseous mixtures based on the size, shape, and equilibrium adsorption capacity of their molecular constituents. Further, the adsorption of unsaturated molecules and molecules with permanent dipole moments is enhanced. Normally, adsorption may be easily reversed by applying heat, displacement molecules, or pressure changes. These reversing processes leave the molecular sieve crystal intact and ready to receive another adsorbent molecule. While the process of adsorption on molecular sieves cannot be accurately characterized by a single isotherm equation, the Langmuir model (7) has been applied to oxygen adsorption, and with modification, to nitrogen adsorption as well. The adsorption of the components of air on molecular sieves follows Type I adsorptive behavior; that is, the amount adsorbed increases rapidly with pressure until a limiting saturation value is reached. Further increase in pressure at constant temperature will not increase the amount of gas adsorbed. At saturation, the internal volume of the molecular sieve crystal is completely filled with adsorbed gas. Desorption of the components of air generally does not show any hysteresis indicating that the adsorption/desorption process is almost completely reversible.

Acid gases, such as hydrogen chloride, sulfur trioxide, and nitrogen dioxide are strongly adsorbed on molecular sieves because of their polarity. Adsorption of these compounds in high concentrations is accompanied by rather high heats of adsorption typical of chemical reactions, which can result in degradation of the molecular sieve crystalline structure. Other gases, such as carbon dioxide, sulfur dioxide and hydrogen sulfide are reversibly adsorbed. In these cases, the heats of adsorption are small, indicating that no chemical reaction is involved. Hydrogen cyanide is a very polar gas which also forms a weak acid. Because of its polarity and physical size, it is thought that hydrogen cyanide cannot be easily desorbed from molecular sieves (1).

Activation of Molecular Sieves

In order to achieve maximum adsorption capacity, initial activation of molecular sieves is necessary to remove water and other contaminants. Water is, by far, the most common substance which can poison or deactivate molecular sieves. Molecular sieves can adsorb significant quantities of mois-

ture due to the water molecule's polarity and small size. In the operation of molecular sieve oxygen generating systems, most moisture in the feed gas is normally vented overboard during the purge and exhaust phase of the operating cycle. If allowed to adsorb, however, water can dramatically affect the adsorptive capacity, or activity of the molecular sieve (6). Hence, for maximum separation efficiency, molecular sieves should have a water content of less than about 1.5 per cent by weight. Two techniques that have been used to activate molecular sieves (by removal of moisture) are vacuum desorption and hot gas purging. Each of these techniques requires heating the molecular sieve to a temperature of about 350 °C. In the vacuum process the pressure is reduced to less than one mm Hg (0.13 kPa), preferably down to 0.001 mm Hg (0.13 Pa), while the temperature of the molecular sieve is held at 350 °C. When the molecular sieve is at these conditions for about four hours, the amount of adsorbate remaining on the molecular sieve is reduced to less than 0.1 weight percent. Since vacuum desorption requires a container that can withstand elevated temperature as well as high vacuum, its use is mainly limited to activation of relatively small quantities of molecular sieve.

Activation of molecular sieve by purging with hot gas is the method of choice for activating the large quantities of molecular sieve required for molecular sieve oxygen generating systems. The molecular sieve material is placed in a steel container, heated to 350 °C and purged with 350 °C nitrogen or dry air at a pressure slightly above atmospheric. Approximately 2 L min^{-1} of hot purge gas is required for each 5 kg of molecular sieve. With 8 to 12 hours of such treatment, the adsorbate moisture content can be reduced to approximately 0.1 weight percent.

Molecular Sieves Employed in Oxygen Concentrators

Presently, most aircraft molecular sieve oxygen concentrator systems use either 5A or 13X zeolite molecular sieve adsorbents (Figure 6.2). The trade name for the molecular sieve containing 5A crystals is "5AMG" and the trade name for 13X based molecular sieve is "OXYSIV-5". (An earlier version of the 13X based molecular sieve was called "MG3"). OXYSIV Type 5 molecular sieve (OXYSIV-5), has become the replacement for MG3. Both 5A and 13X molecular sieves are manufactured by UOP Inc., and both can separate oxygen and nitrogen efficiently, but are unable to distinguish between oxygen and argon. Molecular sieve 5AMG has a nominal pore size (aperture opening) of 4.2 Angstrom, and an equivalent surface area of about 600 $m^2 g^{-1}$. Molecular sieve OXYSIV-5 contains 13X zeolite crystals and has a nominal pore size of 7.4 Angstrom with an equivalent area of about 525 $m^2 g^{-1}$. OXYSIV-5 generally gives better performance in molecular sieve oxygen generating systems and is currently in use in the USAF B-1B and F-15E molecular sieve oxygen generating systems (See Chapter 8).

While both the external surface and internal volume of the molecular size crystal are available for adsorption, the internal volume is available only to those gaseous molecules small enough to enter the pores of the crystal microstructure. Since the external surface constitutes only about 1% of the total surface area, the choice of molecular sieve type for use in aircraft oxygen concentrators may depend on the types and concentration of contaminants foreseen in the aircraft operational environment. Molecular sieves containing the 13X crystal are more effective at removing chemical contaminants from the aircraft engine bleed air (10), and give better concentrator performance (12).

In contrast to zeolite molecular sieves, certain types of carbon molecular sieves have demonstrated an ability to separate oxygen and argon by pressure swing adsorption. This unique capability of carbon molecular sieves led to the development of the High Performance Molecular Sieve Oxygen Generating System (HP-MSOGS)(13,14,15), which can generate oxygen concentrations up to 99.7 percent directly from air. In contrast to zeolites which have a highly uniform pore size, carbon molecular sieves have a pore size distribution generally in the range of 3-9 Angstrom. They are produced by pyrolysis of thermosetting polymers, such as polyvinylidene chloride (PVDC), polyfurfuryl alcohol, cellulose triacetate, and saran copolymer. Some carbon molecular sieves are prepared by the controlled oxidation of coal. The distribution of pore size may be adjusted by changing the conditions of the manufacturing process. Carbon molecular sieves are stable at high temperature and in acidic media, and have a low affinity for water (8, 23). While the High Performance MSOGS is attractive for medical and industrial applications that require very high purity oxygen, the current penalty in throughput makes HP-MSOGS of limited utility for aircraft applications at the present time.

Variations in the oxygen concentrating performance of an oxygen concentrator filled with different batches of the same type of molecular sieve have occurred. Whereas, this was at first assumed to be due to adsorbed water content, it is now thought that the differences probably reflect variations in clay binder content. Techniques for assessing the oxygen-nitrogen separation efficiency of the molecular sieve prior to its use in a concentrator have therefore been developed. The most accurate method involves the direct measurement of adsorption capacity of a small amount of molecular sieve by weight change on a microbalance. This method is time consuming, however, and requires highly accurate weight measurements. To circumvent this shortcoming, an activity tester based on relative adsorption capacity of helium and nitrogen has been developed (15). This device can be used determine the activity of both 5A and 13X based molecular sieves. Another method for evaluation of molecular sieve activity is an oxygen-nitrogen washout technique (6). Both of these methods can be used to assess the activity of new and used molecular sieve beds.

The size of the molecular sieve particles used in most onboard oxygen generating systems is generally 16-40 mesh (US Standard Sieve). This pellet size optimizes the oxygen-nitrogen separation efficiency and minimize pressure drop through the molecular sieve beds. The AV8B aircraft concentrator uses 16-40 mesh 5AMG granular molecular sieve while the B-1B aircraft concentrator employs 16-40 mesh OXYSIV-5 spherical molecular sieve. The "rule-of-thumb" is that the diameter of the molecular sieve particle should be no greater than 1/50th the diameter of the bed.

If molecular sieve pellets migrate within the bed during pressure cycles, their oxygen-nitrogen separation efficiency is reduced and pellet attrition or fracture can occur. This pellet attrition is termed "dusting" because the result is a molecular sieve dust which exits the concentrator through the product and exhaust lines. If allowed to continue, this process may lead to concentrator failure. Generally, an

effective molecular sieve bed containment design will prevent dusting.

Another method to prevent dusting is to immobilize the molecular sieve particles. Molecular sieve immobilization involves the binding together of the molecular sieve pellets with a fluorocarbon polymer to prevent their movement during bed cycling. The pellets are held in place by thin polymer strands. Immobilization appears to improve gas mass transfer characteristics and, under certain conditions, has demonstrated improved oxygen concentrator performance. Studies have shown that immobilized beds produce a dust-free breathing gas at normal operating temperatures. An immobilized OXYSIV-5 molecular sieve oxygen generating system has been flight qualified for the B-1B aircraft (17).

PRESSURE SWING ADSORPTION

Pressure Swing Adsorption (PSA) is the most common adsorption process used for separating oxygen from air. In PSA, the pressure changes occur under essentially isothermal conditions. Hence, the adsorption pressure is always greater than the desorption pressure, and the difference between the two pressures determines the gas loading obtained on the isotherm. An important advantage of PSA is the absence of heating and cooling steps which results in shorter cycle times and also reduces the size of the beds required for gas separation.

The precursor to the molecular sieve oxygen generating system was the heatless adsorption dryer (21). This process employed two fixed beds of adsorbent material that were continually cycled between pressurization (adsorption) and depressurization (desorption). Contaminants or undesirable compounds in the feed gas were concentrated at the front of the bed during adsorption, and stripped from the adsorbent by the purge gas and reduced bed pressure during desorption. The process was applied to air dehumidification and hydrogen purification. The heatless adsorption process was unique in that it eliminated the requirement for heaters for thermal desorption. The modifications required to adapt the heatless adsorption system for concentating oxygen involved changing the adsorbent material to molecular sieve, and optimization of the process cycle time, feed gas pressure and purge flow to accommodate the necessary product flow demand.

AIRCRAFT MOLECULAR SIEVE OXYGEN CONCENTRATORS

The early oxygen concentrators were simply extensions of the heatless adsorption systems. The basic components included molecular sieve beds, inlet control or switching valves, inlet pressure regulator, air filter, check valves, and a purge orifice. In the aircraft application, the concentrator is supplied with conditioned bleed air that is generally derived from one of the high pressure stages of the turbine engine. This air is normally extracted from the aircraft environmental control system, and routed through a particulate or coalescing filter, pressure regulator and inlet valves to the molecular sieve beds.

Molecular Sieve Beds

To produce a continuous flow of product gas, an oxygen concentrator must have at least two beds of molecular sieve (Figure 6.3). The inlet control valve(s) alternately allows air to flow to each bed. As the pressure front passes through the molecular sieve, nitrogen is preferentially adsorbed on the molecular sieve due to its slight polarity. Oxygen and argon compete less effectively for adsorption sites because these molecules are nonpolar. Hence, the air is separated into an oxygen-argon component which elutes first, and a nitrogen component which elutes later (Figure 6.4). Other gases, such as hydrogen, helium and neon which appear at low concentrations in air, also pass rapidly through the bed due to their small molecular size and lack of polarity.

When the objective is to maximize the oxygen concentration, the pressure swing of the bed is timed to permit the oxygen-argon front to exit the bed, while nitrogen is prevented from entering the product gas. A portion of the product gas is used to purge the desorbing bed. This purge gas sweeps out the nitrogen and at the same time fills the micropore structure of the molecular sieve with the product gas. When the bed is repressurized with inlet air, the oxygen-argon gas in the molecular sieve is displaced by nitrogen. The concentration of the oxygen-argon component in the product gas is directly proportional to the fraction of the total product gas used for purge of the desorbing bed. Optimized operation requires that about 80% or more of the total oxygen-argon product gas is used to purge the depres-

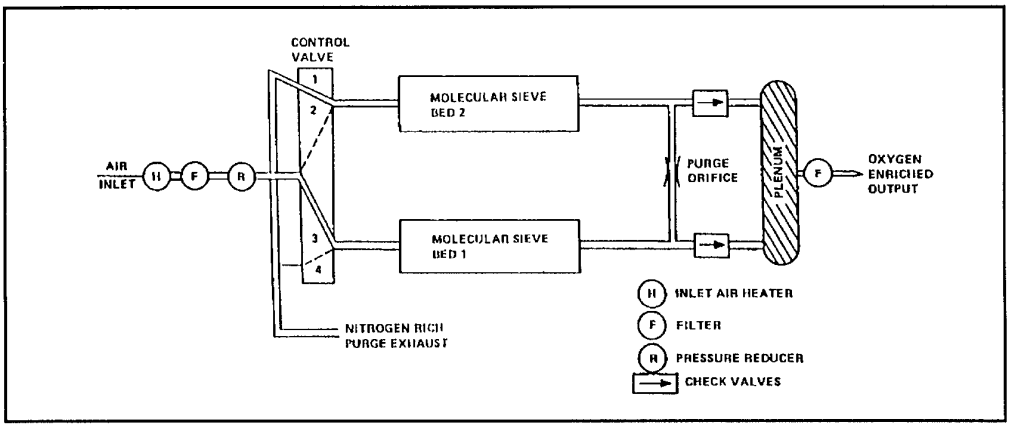

Fig. 6.3 Flow schematic for a typical 2-bed molecular sieve oxygen concentrator.

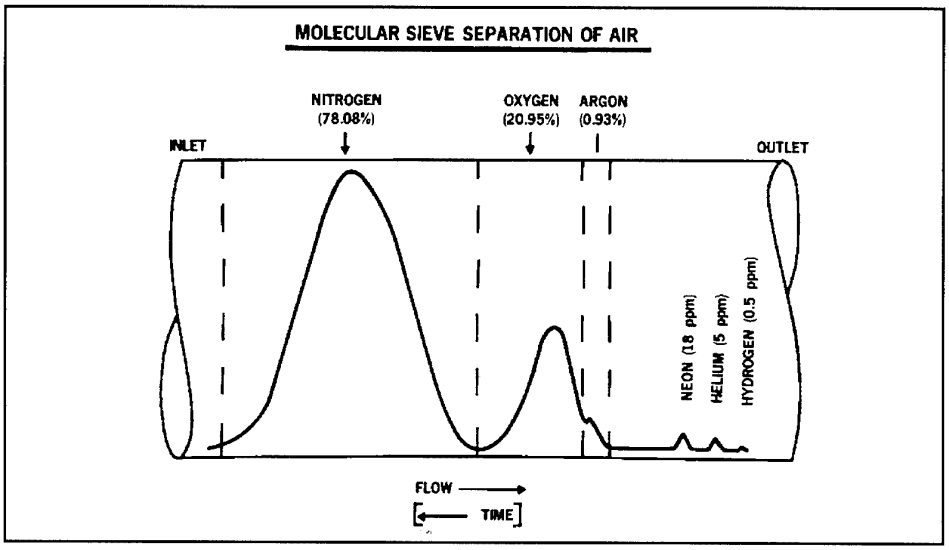

Fig. 6.4 Idealized separation of air on zeolite molecular sieves. Numerical values represent the normal concentrations of the constituents of ambient air (dry).

surized bed. With proper selection of cycle time and purge orifice, a zeolite-based molecular sieve oxygen concentrator will produce a maximum oxygen concentration of approximately 93-95% with the balance being mostly argon.

The molecular sieve beds are the largest components of an oxygen concentrator. The size and shape of beds varies considerably from manufacturer to manufacturer. The shapes used have included square-shaped cylinders, concentric cylinders, split-cylinders, and conical-shaped cylinders. All these bed geometries can be used to separate air. However, certain configurations appear to give better performance. The beds should be uniformly packed with molecular sieve, to minimize interstitial volume. One technique, referred to as "snowstorm" packing, appears to work well for small molecular sieve canisters. Dead space must be minimized to prevent channeling and ensure uniform gas flow through the beds. Molecular sieve pellets must be retained to prevent their movement during the pressure swings, otherwise fracture of the molecular sieve and dusting can result.

Inlet Pressure Regulator and Filter

The inlet regulator controls the air pressure delivered to the beds. In high performance aircraft, the bleed air pressure may be as high as 250 lbf in^{-2} gauge (1720 kPag). In most molecular sieve oxygen generating systems, the engine bleed air is reduced to pressures of 40 lbf in^{-2} gauge (276 kPag) and below. The lowest operating pressure is generally considered to be 20 lbf in^{-2} gauge (138 kPag). Inlet pressures above 40 lbf in^{-2} gauge (276 kPag) result in a negligible improvement in system performance while significantly increasing the air consumption. Ideally, inlet air consumption should be minimized to lessen its impact on aircraft thrust and fuel economy.

The inlet air filter removes particulates including water and oil aerosols. The filter should have an efficiency of 99% for capture of 0.6 micron particles, and removal of oil and water aerosols. While conditioned bleed air is normally of good quality, the inlet filter is essential to protect the beds in the event of loss of an engine oil seal or failure of the water separator in the environmental control system. Since the bleed air may contain oil and water aerosols, the inlet filter should be capable of coalescing these vapors into droplets and draining the residue from the filter element and housing. Liquid water must not contact the molecular sieve. An effective inlet filter is vital for reliable oxygen concentrator performance. Also, an outlet filter for capture of particles $\geq$ 0.1 μ is essential to ensure that particulate free breathing gas is delivered to the aircrew.

Switching Valves

The function of the switching valves is to direct the flow of inlet air into the concentrator beds during pressurization and out of the beds during depressurization. Various mechanisms have been used to direct the gas flow including rotary valves powered by electric (AC or DC) motors, solenoid valves, and solenoid actuated pneumatic valves. The time required for the valves to pass through a bed pressurization and depressurization is termed the cycle time. Generally, MSOCs use a cycle time duration of between 8 and 30 sec.

Heaters

The need for heaters depends upon the operational environment of the aircraft and the efficiency of the environmental control system in providing conditioned air in the temperature range for optimum oxygen-nitrogen separation; i.e., nominally in the range from 0 to 50 °C (Figure 6.5) (9, 12). In some aircraft, heating of the molecular sieve beds may be required during operation in a cold ground environment or during flight at high altitude. Heat can be supplied either by means of a small electric heater located within each bed in direct contact with the molecular sieve, or by passing the inlet air through an electric heater before it enters the MSOC. The disadvantage of the former method is that it does not distribute the heat uniformly which may reduce separation efficiency. A covering of insulation around the concentrator may be beneficial for temperature control.

Factors Affecting the Composition and Pressure of the Product Gas

Critical factors affecting the composition and pressure of the breathing gas produced by a molecular sieve oxygen concentrator include the inlet air pressure, concentrator temperature, product gas flow, molecular sieve activity, and cycle time (18). The exhaust gas from the oxygen concentrator is always vented to the ambient pressure at the aircraft altitude.

The pressure of the product gas is largely dependent on the air pressure supplied to the concentrator. Most oxygen concentrators require an air pressure of 20 lbf in^{-2} gauge (138 kPag) or greater (referenced to aircraft ambient pressure) for satisfactory performance. A drop in air supply pressure to 10-15 lbf in^{-2} gauge (69-103 kPag) can significantly affect system performance. Also, breathing regulators designed for MSOGS do not function properly at inlet pressures below about 5 lbf in^{-2} gauge (34 kPag), referenced to cabin pressure. In designing MSOGS for a particular aircraft one must consider the bleed air pressure at all points in the flight envelope. Potential problem areas include ground idle, taxi, and engine-idle descent from altitude when bleed air pressure may be minimal.

Loss of molecular sieve activity may reduce the concentration of oxygen in the product gas. The major cause of loss of activity is water adsorption. Water is held very strongly in the micropore structure of the molecular sieve, thereby reducing its ability to adsorb nitrogen. However, time of contact is critical. Laboratory studies conducted at ground level have shown that product oxygen concentration may not be seriously affected until more than 50% of the bed has been deactivated with water (6). The air supply to an oxygen concentrator can contain relatively large quantities of water vapor and yet not cause significant deactivation of the molecular sieve beds. This result occurs because the short cycle time ensures that most water entering the bed during the pressurization phase is removed during the depressurization and purge phase. If the pressure in the molecular sieve beds is not cycling, however, there may be sufficient time for water to enter the microstructure of the molecular sieve and be adsorbed strongly. Hence, whenever air pressure is supplied to a concentrator, the molecular sieve beds must be cycling or a significant amount of deactivation may occur.

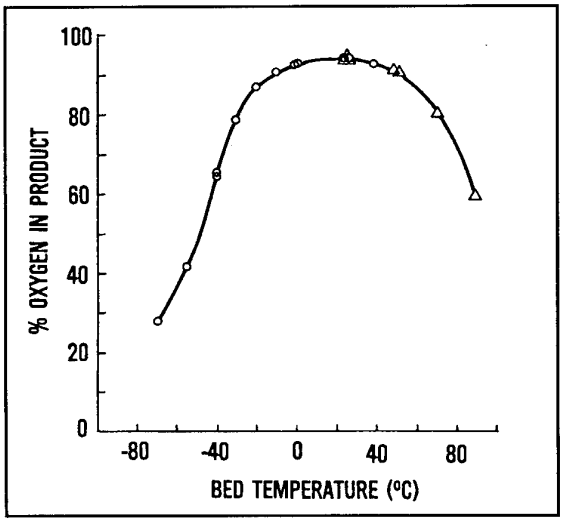

Fig. 6.5 Oxygen concentration from molecular sieve oxygen concentrator as a function of bed temperature. Data taken from Miller (9,11).

For a given design of oxygen concentrator, there is an optimum cycle time which maximizes the oxygen concentration for a given product flow. Shortening the cycle time below this optimum value decreases the concentration of oxygen since the oxygen wave front does not have sufficient time to propagate through the molecular sieve bed, and the gas flow is reversed before the oxygen wave front reaches the end of the bed. If the cycle time is lengthened beyond the optimum time, the oxygen concentration decreases because nitrogen breaks through into the product gas. If air pressure is applied and the beds are not cycling, the bed receiving the air flow will eventually become saturated with nitrogen and no gas separation will occur.

Increasing the flow of product gas from the concentrator results in a progressive reduction of the concentration of oxygen. The increasing flow of product gas eventually causes the nitrogen wavefront to break through into the product gas. High oxygen concentrations are obtained by decreasing the flow of product gas, thereby allowing a sufficient quantity of purge gas to enter the depressurized bed.

The efficiency of a molecular sieve oxygen concentrator decreases when the temperature of the molecular sieve is below 0 °C or above 50 °C (Figure 6.5). When the bed temperature is below 0 °C, oxygen concentrator performance can be improved by lengthening the cycle time (12). Similarly, the drop in oxygen concentration caused by bed temperatures above 50 °C can be partially offset by shortening the cycle time. However, cycle time changes at low or high temperature do not fully restore the concentrator to optimum performance. Low temperature operation reduces the diffusivities of both oxygen and nitrogen, and increases the molecular sieve adsorptive capacity for nearly all gases including oxygen and nitrogen. At low temperatures, the cycle time must be increased to compensate for changes in gas diffusivity and adsorption capacity. Even though the adsorption capacity of the molecular sieve is increased at low temperature, the slower nitrogen desorption prevents the oxygen concentration from reaching its maximum value.

The fall in oxygen concentration caused by a temperature above 50 °C is due to a reduction in nitrogen adsorption capacity of the molecular sieve. Nitrogen breakthrough occurs before the flow in the bed is reversed. Decreasing the cycle time at higher temperature will improve performance by limiting the penetration of the nitrogen wave front. Under these conditions, the oxygen concentration is increased but the lower capacity of the bed prevents optimum operation.

Small Molecular Sieve Oxygen Concentrator

Small molecular sieve oxygen concentrators (Small MSOCs) are used to circumvent the problems of handling large volumes of contaminated feed and exhaust gas in evaluating the effects of chemical warfare agents and other contaminants on molecular sieves (22). Compared to a full scale molecular sieve oxygen generating system, Small MSOCs may contain as little as 4% of the molecular sieve and require only about 10% of the process air. These devices are constructed of stainless steel and designed for easy disassembly, wash and decontamination (Figure 6.6). The performance charac-

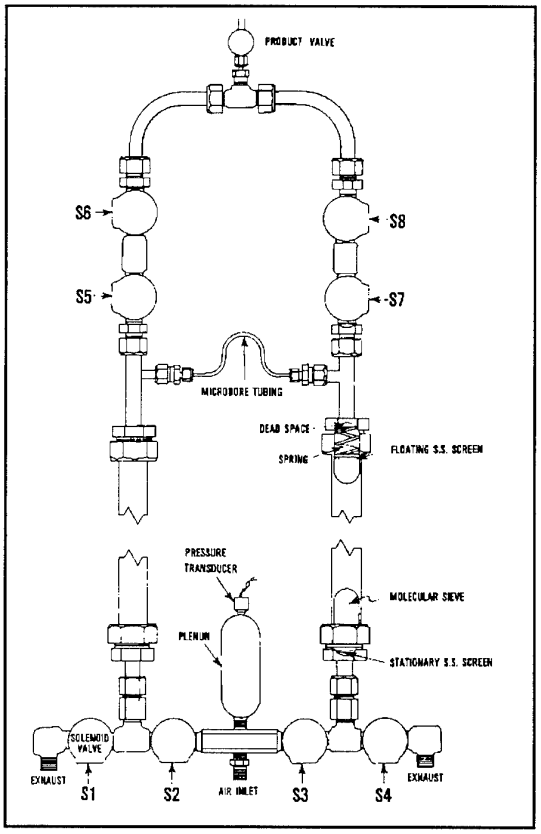

Fig. 6.6 Small Molecular Sieve Oxygen Concentrator (22).

teristics of small units are very similar to those of a full scale MSOGS. Both types of concentrators deliver an oxygen concentration of 94% at low product flows, become less efficient in gas separation with increasing or decreasing temperature, and show a decrease in oxygen concentration with increasing product flow. A small MSOC is a low cost, convenient method for studying the effects of contaminants. However, small-scale testing should not replace full-scale testing of aircraft MSOC designs for the verification of chemical agent protection capabilities.

Mathematical Modeling

Computer models of molecular sieve oxygen concentrators have been developed to improve the understanding of operating and scaling laws. Beaman et al (3) formulated and verified a model of a single molecular sieve bed which accurately predicted the transient response of gas flow and gas concentration at the outlet of the bed in response to sudden changes in the composition at the gas at the inlet. Predicted oxygen and nitrogen breakthrough times were validated in a single bed packed with 5AMG molecular sieve. In these experiments, the bed was initially saturated with one of these gases and then a constant inlet flow of the other gas was allowed to flow into the bed. The outlet oxygen concentration and mass flow were recorded at several inlet pressures and flows. The model predictions agreed with the experimental data when a linear adsorption isotherm was used for oxygen, a nonlinear Langmuir isotherm for nitrogen, and the two isotherms were coupled.

Beaman also developed a relatively simple isothermal model of a pressure swing adsorption oxygen generating system which was applicable to the Litton oxygen concentrator employed in the AV-8A/B aircraft (4). The object of this model was to predict the concentration of oxygen in the product gas given the demand flow. This goal was accomplished by modeling the rotary valve, purge orifice, the two molecular sieve beds and the breathing gas plenum, and coupling these separate models into an overall system model. Using the model to determine the oxygen concentration at various conditions requires the definition of 16 parameters, grouped into three categories: system parameters, geometric parameters, and bed parameters. System parameters include air supply pressure, outlet pressure, running time, cycle time, and breathing flow rate. The geometric parameters include purge orifice diameter, supply valve diameter, outlet valve diameter, bed length, outer and inner bed diameters in the case of concentric cylindrical geometry, or other bed measurements for different geometric configurations. The bed parameters are specific to the type of molecular sieve employed and include such parameters as void fraction, isotherm coefficients, and diffusion coefficients.

Munkvold et al (20) modified the Beaman computer model to accommodate step changes in the demand of breathing gas between low and high flows. The model will predict the oxygen concentration before, during and after a step change in flow rate. The model predictions compare favorably with experimental results and have been used in design and control studies.

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Chapter 7

BREATHING GAS REGULATORS AND MASKS FOR ADVANCED OXYGEN SYSTEMS

John Ernsting

INTRODUCTION

The adoption of molecular sieve oxygen concentrators in place of liquid oxygen storage to provide breathing gas in Advanced Oxygen Systems necessitates major changes in the design of the associated pressure demand delivery system. In parallel, the increase in the sustained high $+G_z$ acceleration performance of agile combat aircraft requires that Advanced Oxygen Systems for these aircraft provide pressure breathing with $+G_z$ acceleration. An Advanced Oxygen System should also incorporate all the features required to ensure aircrew breathing comfort and protection (Chapter 5 refers), to enhance flight safety and to overcome the deficiencies of conventional oxygen systems (Chapter 2 refers).

The major components of the breathing gas delivery system of an Advanced Oxygen System are the pressure demand regulator, the aircrew breathing mask (or aircrew NBC respirator) and the associated hoses and connectors. Many of the aspects of the performance of an Advanced Oxygen System are determined by the integrated behaviour of these components. The requirements for the breathing gas delivery system of an Advanced Oxygen system, together with the design and performance of components which have been developed to meet these requirements, are considered in this chapter.

It became apparent during the late 1940s and early 1950s that it was unsatisfactory to determine the pressure-flow characteristics of breathing gas delivery systems only under steady flow conditions. The dynamic responses of several components of a delivery system may be inadequate to meet the rapidly changing flows which occur during respiration, especially during work, speech and air combat (Chapter 5 refers). It is now accepted practice to specify and to measure the pressure-flow characteristics of breathing gas delivery systems in dynamic terms, as illustrated by the present ASCC and NATO requirements for the performance of aircrew breathing systems (1,7).

ARRANGEMENT OF COMPONENTS OF BREATHING GAS DELIVERY SYSTEMS

Duplication of Components

The breathing gas delivery system employed in an Advanced Oxygen System must have a high reliability, especially as the altitudes at which future agile combat aircraft will operate may be considerably higher than present day aircraft, and hence aircrew may well be exposed routinely to higher cabin altitudes than they have in the last three decades. Whilst the principal method of achieving reliability is to ensure, by design and exhaustive systematic testing, that the probability of essential components such as regulators, valves and connectors failing in flight is extremely low, it is also possible to increase the overall safety of the breathing gas delivery system by duplication of essential components. This philosophy has been followed in various ways in the past. Thus in many panel mounted oxygen regulator systems, the emergency oxygen supply is connected into the main system at, or immediately upstream of, the mask inlet hose connector (Chapter 2 and Figure 2.1 refer), so that the delivery of an alternative supply of oxygen is independent of the pressure demand regulator. Some seat mounted pressure demand regulator systems have two demand regulators within the regulator package so that an alternative regulator can be selected in the event of a malfunction of the primary regulator (Chapter 2 and Figure 2.4 refer). Testing of breathing gas delivery systems and practical experience of their use in combat aircraft supports the current design principles that no duplication of the inlet hose or of the valves of the mask is required, but that duplication of the pressure demand regulator should be considered. Duplication of the regulator has been the practice in the Royal Air Force since the 1960s. It is possible, especially in seat mounted regulator systems, to provide by means of a second regulator, the ability to complete a mission following a failure of the primary regulator. This approach has, however, not been employed in breathing gas delivery systems designed for use in high performance combat aircraft in the United States. The Advanced Oxygen System under development for Eurofighter 2000 has a dual pressure demand regulator package mounted on each ejection seat.

Location of components

The performance of a breathing gas delivery system and the associated in-flight aircrew drills are influenced considerably by the location of the pressure demand regulator, and the manner in which the outlet of the latter is connected to the inlet port of the aircrew mask (or aircrew NBC respirator). The three major sites which are employed for mounting the pressure demand regulator in present and projected agile combat aircraft are in a side console of the cockpit, on the side of the ejection seat and on the front of the chest of the aircrew member. Console mounting of the regulator is associated with the greatest physical separation of the mask from the regulator and from the Emergency Oxygen supply on the ejection seat. Chest mounting of the regulator provides the shortest distance between mask and regulator but the regulator is still a significant distance from the Emergency Oxygen supply on the ejection seat or in the personal survival pack. This arrangement can, however, have the lowest resistance to flow from the outlet of the regulator to the inlet port of the mask and the volume of the hose between these two points will be minimal (120 -150 ml). Seat mounting of the regulator requires only a moderate distance between the mask and regulator, with the volume of the low pressure delivery system between the regulator and the inlet port of the mask being of the order of 450 ml. The resistance to flow between the two sites can be minimised by the use of wide (19 mm) smooth bore hose. Seat mounting of the pressure demand regulator also allows full integration of the controls of the regulator and the Emergency Oxygen and back-up oxygen (if the latter is mounted on the ejection seat), particularly if the pressure demand regulator is duplicated.

Connectors are required in the breathing gas delivery system between those components mounted on the aircrew member which, at a minimum, is the aircrew mask (or aircrew NBC

respirator) and those components mounted on the airframe and ejection seat. Ideally these connections are locked when made, so that they cannot separate in routine flight. A purposeful act should be required to unlock the connections on leaving the cockpit but they should be unlocked automatically at the appropriate time during the ejection sequence. All these requirements are met by the use of a personal equipment connector which carries all the personal services [oxygen, anti G air and Radio/Telephone] between the airframe and the personal equipment worn by the aircrew member. This connector can be mounted on the ejection seat or on the personal survival pack (Rigid Seat Survival Kit) within the seat. An additional locking connector is required to allow the mask and helmet to be donned and removed separately from a personal oxygen hose assembly or a chest mounted regulator. The use of a personal equipment connector also eliminates the requirement for the aircrew member to connect/disconnect the emergency oxygen supply into the main system on cockpit entry/exit. In low pressure delivery systems in which a pull-off connector is employed for routine entry and routine and emergency exit, the man portion of the connector should impose a high resistance to inspiration on disconnection, to warn of a failure to connect or of an inadvertent disconnection in flight.

PRESSURE DEMAND REGULATORS

Although the overall performance of a breathing gas delivery system depends upon all the components, there are many aspects which depend primarily on the design and performance of the pressure demand regulator. These aspects of the breathing gas delivery system for an Advanced Oxygen System for an agile combat aircraft are considered in the following paragraphs.

In considering the contributions of the components of the breathing gas delivery system to the overall performance of the system, it has become the convention for practical purposes to consider the performance of the pressure demand regulator and low pressure gas delivery system up to and including the mask hose connector as a single unit. Thus many specifications define the performance of breathing gas delivery systems at this point, which is generally termed the mask hose. The performance of the inspiratory components of the mask is then defined in the mask cavity in relation to the conditions at the free end of the inlet hose to the mask ie. the mask tube.

Supplies to the Pressure Demand Regulator

The gas supplied to the pressure demand regulator provided by a molecular sieve oxygen concentrator differs in two major respects from the gas provided in a conventional oxygen system with a liquid oxygen store. The gas supplied by a molecular sieve oxygen concentrator is most often a mixture of oxygen, nitrogen and argon in which the concentration of oxygen has already been controlled to that required in relation to the prevailing cabin altitude, so that no admixture with cabin air is required in the breathing gas regulator. This provision of gas of the required composition allows considerable simplification of the breathing gas regulator and of the associated aircrew drills. In some molecular sieve oxygen generating systems however, such as that fitted to the F-15E (Chapter 8 refers), the gas supplied to the breathing gas regulator contains 93-95% oxygen and the regulator provides controlled admixture with cabin air. This arrangement is very similar to that of a conventional air dilution regulator with the air dilution profile modified to take account of the 93-95% oxygen which replaces the >99.5% oxygen of a conventional oxygen system. This approach, whilst not providing simplification of the breathing gas regulator, allows the retention of the aircrew drills associated with a conventional oxygen system; the possibility that the oxygen concentration in the gas supplied by the oxygen concentrator may fall below 93% has, however, to be allowed for.

The other major difference is the pressure at which gas is supplied to the breathing gas regulator. The pressure at which a molecular sieve oxygen concentrator supplies product gas is determined primarily by the pressure at which conditioned engine bleed air is supplied to the concentrator (Chapter 6 refers). The latter varies considerably from one aircraft to another, depending upon the bleed air characteristics of the engine(s) and the performance of the environmental control system. The pressure at which product gas is delivered at the outlet of the molecular sieve oxygen concentrator is typically 25-35 lbf $in^{-2}g$ (172-241 kPag). The pressure at which the product gas is delivered to the inlet of the breathing gas regulator relative to the absolute pressure in the pressure cabin will, however, be less than these figures by the differential pressure of the pressure cabin, which will usually amount to 5 lbf $in^{-2}g$ (34.5 kPa) at aircraft altitudes above 23,000 feet. The pressure at which the molecular sieve oxygen concentrator delivers product gas may fall below the nominal value of 25 - 35 lbf $in^{-2}g$ (172-241 kPag) when the engine(s) are set to idle power either on the ground or during descent from altitude. The minimum pressure of the gas supplied to the inlet of the regulator in these circumstances may be as low as 5 lbf $in^{-2}g$ (34.5 kPag). This possibility is recognised in the current NATO standard which allows a decrease in the peak inspiratory flow which the complete system is required to meet from 200 L (ATPD) min^{-1} to 90 L(ATPD) min^{-1} at low engine power settings (7).

The breathing gas delivery system will also be supplied with stored gas from the Back-up or Emergency Oxygen Supply following failure of the oxygen concentrator to provide product gas of an acceptable composition and/or at an acceptable pressure. This gas, which is stored at relatively high pressures (400 - 1,800 lbf $in^{-2}g$ (2,760-12,400 kPag)), is passed through a reducing valve before it is delivered to the breathing gas regulator, usually at a pressure of 40 - 60 lbf $in^{-2}g$ (276-413 kPag).

Flow Capacity and Resistance to Breathing

The breathing gas delivery system should have the flow capacity to meet peak inspiratory and expiratory flows of at least 200 L (ATPD) min^{-1} with rates of change of flow of at least 20 L (ATPD) sec^{-2} at all altitudes whilst not imposing resistance to breathing (in terms of the total change of pressure in the mask cavity during the respiratory cycle) in excess of the limits specified in current ASCC and NATO standards (1,7) (Chapter 5 refers). In order to meet these requirements, the changes of pressure which occur at the outlet of the pressure demand regulator during cyclic demands, the resistance to flow from the outlet of the regulator to the mask and the resistance to flow through the valves of the mask itself should be minimal. In general, the contribution of the current generation of pressure demand regulators to the overall resistance to breathing of the oxygen

system is relatively small (Chapter 2 refers). There are, however, several areas in which improvements are required with respect to the resistance imposed by the regulator, particularly at low supply pressures. In order to meet the current ASCC and NATO standards, the breathing gas regulator should ideally be capable of passing a flow of 200 L (ATPD) min^{-1} at ground level when the inlet pressure to the regulator is the minimum which may occur either on the ground or in flight. As already noted, it may not be possible in some aircraft installations to meet this requirement when the engine(s) are set at idle (7).

The designs of demand valves employed in panel mounted pressure demand regulators where the demand valve is held shut by the force of a spring are optimised for a relatively high and relatively constant pressure of the gas immediately upstream of the demand valve - of the order of 40 - 50 lbf $in^{-2}g$ (276 - 345 kPag). It is possible to modify the design of this type of regulator so that it operates effectively at lower inlet pressures as in the MSOC system for the F-15E in which the flow of product gas is controlled by the panel mounted CRU-98/A pressure demand regulator, which operates at inlet pressures down to 20 lbf $in^{-2}g$ (138 kPag) (Chapter 8 refers). Several pressure demand regulators are capable of delivering high flows of product gas at the very low inlet pressures (5 lbf $in^{-2}g$ (35 kPag)) which can occur in some MSOC systems and which will also operate at the higher inlet pressures (up to 120 lbf $in^{-2}g$ (827 kPag)) which occur in liquid oxygen systems. The essential feature of these regulators is the balanced demand valve (Figure 7.1) in which the inlet pressure applies equal and opposing forces on the demand valve - one forcing the valve open and the other forcing it shut. The forces required to hold a balanced demand valve shut and to open it are relatively small and almost independent of the inlet pressure. The total swing of pressure during cyclic demand at the mask tube with this type of pressure demand regulator (seat or chest mounted) at inlet pressures between 15 and 120 lbf $in^{-2}g$ (103 - 827 kPag) is typically 0.6 inch wg (0.15 kPag) at a peak flow of 30 L(ATPD) min^{-1} and 2.5 inch wg (0.63 kPag) at a peak flow of 200 L(ATPD) min^{-1}. At an inlet pressure of 5 lbf $in^{-2}g$ (35 kPag) the swing of mask tube pressure at a peak flow of 70 L(ATPD) min^{-1} is typically only 1.5 inch wg (0.38 kPag).

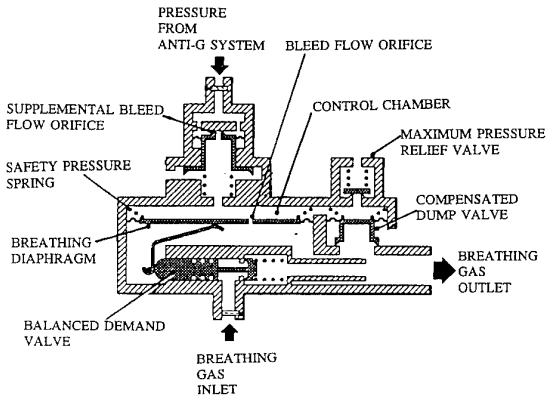

Fig. 7.1 A schematic diagram of a low inlet pressure breathing gas regulator with a balanced demand valve providing safety pressure and pressure breathing with G. Pressure breathing with altitude and "press-to-test" facilities are not included (6).

Safety Pressure

The presence of safety pressure in the mask cavity provides excellent protection against an ill-fitting mask allowing cabin air to be inhaled, thereby producing hypoxia at altitudes above 15,000 feet or toxic fumes/smoke/BCW agents in the cabin air to enter the respiratory tract at any altitude. The presence of safety pressure also increases breathing comfort. The permanent provision of safety pressure at all altitudes, instead of providing it only above an altitude of 15,000 or 30,000 feet and on manual selection, as is done in several conventional oxygen systems (Chapter 2 refers), greatly simplifies the design of the breathing gas regulator. Advanced Oxygen Systems for high performance combat aircraft should therefore provide safety pressure at all altitudes. The only disadvantage of this approach is that there will be a high flow of gas from the mask when the latter is removed from the face. This high flow of product gas may in some systems reduce the PO_2 of the gas to a level at which the low PO_2 warning operates and this may result in selection of the Back-up or Emergency Oxygen Supply, which will be rapidly exhausted. Methods of avoiding this disadvantage of permanent safety pressure are discussed in Chapter 10.

The performance of the breathing gas delivery system should be such that the pressure in the mask cavity is maintained greater than that of the environment at inspiratory flows of up to at least 70 L (ATPD) min^{-1} [85 L(ATPD) min^{-1} when an aircrew NBC respirator is worn]. The maximum pressures in the mask during the respiratory cycle are not to exceed those specified in the ASCC and NATO standards (1,7) (Chapter 5 refers). Safety pressure is provided in modern pressure demand regulators designed for use in MSOC systems by a spring which acts upon the breathing diaphragm of the regulator (Figure 7.1), thus raising the datum pressure around which the sensing diaphragm and demand valve operate. This method of providing safety pressure is simple, effective and very reliable.

Limitation of Maximum Mask Pressure

As is discussed in a later paragraph, the aircrew mask or the mask of an aircrew NBC respirator used in an Advanced Oxygen System will be fitted with a conventional inlet non-return valve and compensated outlet valve system. For expired gas to flow through the outlet valve requires that the pressure in the mask cavity is raised above that in the mask tube. An increase of pressure in the mask tube produced by mask hose pumping or rapid ascent will cause a rise of mask pressure during expiration (Chapter 2 refers). In order to limit this rise of pressure to less than 1.0 inch water gauge (0.25 kPa) as required by the current NATO standard (7), the rise of pressure in the mask tube in these conditions must be similarly limited. This facility can be provided by fitting a dump valve at the outlet of the breathing gas regulator, the opening of which is controlled by appropriate spring loading and compensation pressure (Figure 7.1). The dump valve will also limit an excessive rise of mask tube pressure induced by a high rate of decrease of demand for flow, such as occurs on inspiration during speaking, and when performing the anti-G straining manoeuvre.

Lung damage due to a high flow failure of the demand valve of the regulator which in a conventional system will produce a very rapid and excessive rise of mask and hence transpulmonary pressure, can also be prevented by a

compensated dump valve at the outlet of the regulator, provided that the dump valve has an adequate flow capacity. The dump valve should be capable of limiting the mask cavity pressure to a maximum of 41 mm Hg (5.5 kPag) when the demand valve is fully open (1,7). Some compromise may be necessary in this context, as the size of the dump valve required to limit the pressure to this value may be excessive. In any case, the pressure in the mask cavity in the event of a full flow failure of the demand valve should not exceed 60 mm Hg (8 kPag).

The rise of mask cavity and hence transpulmonary pressure produced by a rapid decompression of the cabin can also be limited by a dump valve at the outlet of the breathing gas regulator. The dump valve will allow the gas expanding in the hose between the regulator and the inlet valve of the mask to escape to ambient, and thus limit the rise of mask tube pressure produced by the rapid decompression. Provided that the flow capacity of the compensated outlet valve of the mask is adequate, lung damage on rapid decompression can be prevented by limiting the maximum mask tube pressure to 41 mm Hg (5.5 kPag) (Chapter 5 refers).

The outlet of the breathing gas regulator of an Advanced Oxygen System should therefore include a dump valve which allows excess gas to escape from the mask hose whenever the pressure in the latter exceeds the nominal delivery pressure of the regulator. The opening of the dump valve is controlled by spring loading and the application of a compensating pressure. The dump valve is held shut during the delivery of pressure breathing (at altitude, with $+G_z$ and on press-to-test) by the application of the control pressure used to load the breathing diaphragm (Figure 7.1). An excessive rise of the control pressure applied to the breathing diaphragm and the compensation chamber of the dump valve of the regulator due to a failure of, for example, the pressure breathing aneroid, must be prevented. This facility is provided by a spring loaded maximum pressure relief valve (Figure 7.1) which will prevent the pressure in the control chamber exceeding an acceptable level.

Pressure Breathing at Altitude (PBA)

Short duration protection against hypoxia can be provided by pressure breathing with a mask alone at altitudes up to 50,000 feet. Protection at higher altitudes requires the application of counterpressure to chest, abdomen and lower limbs (Chapter 5 refers). Pressure breathing with a well sealing mask, and counterpressure to the trunk and lower limbs, will provide short duration protection at altitudes up to 60,000 - 65,000 feet where a breathing pressure of the order of 70-75 mm Hg (9.3 - 10 kPag) is required. It is highly desirable that the pressure breathing system employs a pressure breathing mask which automatically seals the high breathing pressures (see below). Manual control of the tension in the mask harness is, however, acceptable if it can be applied rapidly and reliably.

Counterpressure to the chest is applied by means of a counterpressure garment. The bladder of the garment is simply connected into the mask hose between the outlet of the breathing gas regulator and the inlet valve of the mask (Figure 7.2). Counterpressure is applied to the abdomen and lower limbs by inflating the G trousers to a pressure which is 2.0 - 2.5 times breathing pressure (UK Standard).
The required relationship between breathing pressure and altitude (Chapter 5 refers) is obtained from the breathing gas regulator by an aneroid acting on the breathing diaphragm either through a system of mechanical levers or, more usually, by raising the pressure of the gas on the control surface of the breathing diaphragm. The bleed flow of product gas required to generate the increase in pressure in the control chamber of the regulator is provided either by a tapping taken from the inlet of the regulator or through a small orifice in the breathing diaphragm (Figure 7.1).

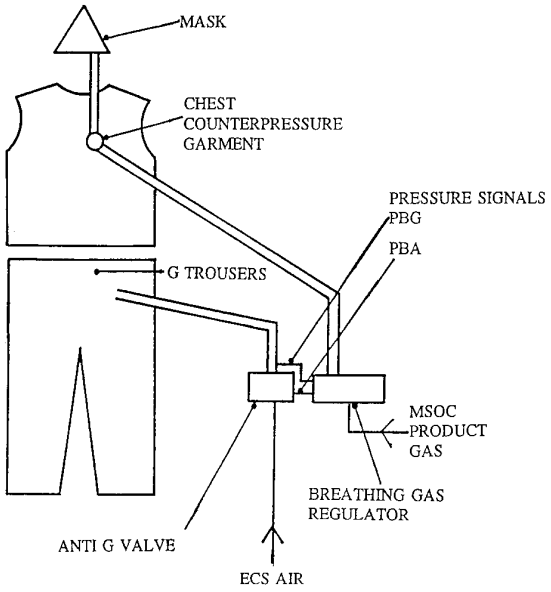

Fig. 7.2 A diagram of the layout of the major components of a typical pressure breathing with G (PBG) and pressure breathing at altitude (PBA) aircrew equipment assembly, and the connections to the breathing gas regulator and the anti G valve supplying the assembly.

The bleed flow escapes freely to ambient at altitudes below 40,000 feet and the pressure in the control chamber of the regulator remains at ambient until the pressure breathing aneroid expands and, at altitudes above 40,000 feet, produces the required increase of pressure in the control chamber and hence at the outlet of the regulator. The gas loading is also applied simultaneously to the compensation chamber of the dump valve at the outlet of the regulator.

The compensated dump valve limits the rise of pressure which occurs in the mask tube on rapid decompression. It may also limit the maximum pressure in the chest counterpressure garment, although the limited flow capacity of the dump valve may not provide adequate venting of gas from the garment which may be inflated to pressure (PBG) prior to a decompression. It may be necessary to fit an inlet valve and compensated outlet valve assembly to the chest counterpressure garment, in order to prevent an excessive rise of pressure in the garment on a rapid decompression. Over-pressurisation of the chest counterpressure garment may, however, provide some protection against over-distention of the lungs on a rapid decompression. Such a compensated valve system on the garment may increase the consumption of product gas both in the presence of safety pressure and during pressure breathing, as the changes in the volume of the garment during the respiratory cycle result in gas escaping to ambient through the compensated outlet valve.

The G trousers, as part of the altitude partial pressure assembly, are usually inflated with engine bleed air through an anti G valve. A pneumatic signal is taken from the outlet of the breathing gas regulator and applied through a diaphragm and spring arrangement to the control mass or control diaphragm of the anti G valve with the area relationships required to provide a pressure in the G trousers which is 2.0 to 2.5 times the breathing pressure (Figure 7.2). In this arrangement, a failure of the supply of bleed air, which is a possible cause of loss of cabin pressurisation at high altitude [although the leaktightness of the cabin should prevent the cabin altitude exceeding 40,000 feet in the event of flame-out of the engine(s) at maximum altitude] could result in inadequate inflation of the G trousers. Special consideration also has to be given to the maintenance of the desired pressure in the G trousers after ejection at high altitude. It may be possible to ensure adequate pressurisation of the G trousers during the subsequent descent in the seat by ensuring that the G trousers are inflated prior to ejection, and that no gas can to escape from the G trousers following the ejection. An alternative is to provide a small supply of compressed air on the seat to maintain the inflation of the G trousers.

Pressure Breathing for $+G_z$ Protection (PBG)

Pressure breathing with chest counterpressure greatly enhances the protection afforded by inflated G trousers and the Anti-G Straining Manoeuvre and should be provided in all agile combat aircraft in which the aircrew will be exposed to sustained $+G_z$ accelerations in excess of 6 - 7G (Chapter 5 refers). The provision of pressure breathing with G (PBG) must be dependant on the effective pressurisation of the G trousers. A pneumatic signal taken from the anti G system between the outlet of the anti G valve and the G trousers is used to induce pressure breathing in the breathing gas delivery system (Figure 7.2). Pressure breathing should probably commence at an acceleration level of 4 - 4.5G. The maximum breathing pressure is, on present evidence, a pressure of 60-65 mm Hg (8.0-8.7 kPag) at 9G (Chapter 5 refers). It is essential that the oronasal mask seals during pressure breathing so that the maintenance of a good mask seal requires no action by the aircrew member.

Counterpressure is applied to the chest by inflation of the bladder of a chest counterpressure garment in the same manner as described for pressure breathing at altitude (Figure 7.2). Indeed, the same partial pressure clothing assembly is employed for pressure breathing at altitude and at high $+G_z$. The embodiment of an inlet valve and a compensated dump valve at the inlet to the garment, which ensures that the pressure in the chest counterpressure garment falls rapidly as the pressure in the mask tube falls, is of considerable value in pressure breathing with G - otherwise the gas which is contained in the bladder of the chest garment has to be breathed away which only provides slow deflation of the garment on cessation of the exposure to increased $+G_z$ acceleration [a proportion will vent to ambient through the dump valve at the outlet of the breathing gas regulator].

The passage of the signal from the outlet of the anti G system to the breathing gas regulator requires a pneumatic connection between these two items (Figure 7.2). In a system in which both the pressure demand regulator and anti G valve are mounted in the cockpit console, this connection can be permanent although its path may be long. In systems employing a seat mounted pressure demand regulator, the signal may be taken either from the G trouser port of the personal equipment connector or directly from the anti G valve, should this also be seat mounted. The breathing gas pressure demand regulator and the anti G valve can be combined into a single unit which can be mounted on the side of the ejection seat (or the cockpit console). When the pressure demand regulator is chest mounted, the signal can be taken directly from the G trousers. This will require, however, that the aircrew member makes this connection whilst dressing.

Pressure breathing on exposure to $+G_z$ is induced in pressure demand regulators by applying gas loading to the breathing diaphragm of the regulator, the magnitude of which is controlled by the pressure signal from the anti G system (G trouser pressure). The G trouser pressure restricts the venting of the bleed flow gas to ambient by means of a diaphragm or piston acting upon a valve plate which controls the vent to ambient (Figure 7.1). The onset of pressure breathing is delayed until the G trouser pressure rises to that produced by 4 - 4.5 G (typically 4.0 - 4.6 lbf $in^{-2}g$ (28 - 32 kPag)) by the force of a spring which has to be overcome before the diaphragm or piston begins to restrict the venting of the bleed flow to ambient (Figure 7.1). The relationship between breathing pressure and G trouser pressure is determined by the ratio of the area of the diaphragm or piston exposed to G trouser pressure to the area of the valve plate controlling the vent of the bleed flow to ambient. In some PBG regulators, a supplemental bleed of air from the anti G system is used to increase the rate at which pressure breathing is produced by the breathing gas regulator (6). In other types of regulator an additional diaphragm, the follower diaphragm, is employed in the mechanism for gas loading of the breathing diaphragm. This feature is required to minimise the swing of regulator outlet pressure during pressure breathing with G.

Press-to-Test

Having made all the connections between the personal equipment and the aircraft supply systems, the aircrew member should be able to induce pressure breathing to check the integrity of the system, the seal of the aircrew mask (or aircrew NBC respirator) and the connections in the breathing gas delivery and the G trouser inflation systems. When an altitude partial pressure assembly and/or pressure breathing with G assembly is worn, then this test procedure requires the delivery by the pressure demand regulator of a breathing pressure of 50-60 mm Hg (6.7 - 8 kPag). It is not desirable to produce this level of pressure breathing by inflation of the G trousers to the pressure [8 - 10 lbf $in^{-2}g$ (55 - 69 kPag)] which produces pressure breathing in flight at high $+G_z$ as the high G trouser pressure will induce severe discomfort at 1G. A more satisfactory method is to induce pressure breathing in the regulator and to utilise the pneumatic link to the anti G valve provided for pressure breathing at altitude to inflate the G trousers to 2.0 to 2.5 times breathing pressure.

Pressure breathing for testing the system at ground level is induced in the breathing gas regulator by applying the appropriate force to the breathing diaphragm either by a mechanical lever and spring system as in some panel mounted regulators, or, more commonly, by gas loading. The pressure in the control chamber of the regulator (Figure 7.1) is raised by closing the normal vent of the bleed flow to ambient. The level to which the pressure in the chamber

increases is controlled by a press-to-test relief valve which opens at a pressure of 27 - 32 inch wg (6.8 - 8.0 kPag).

Breathing Gas Regulator Controls

A breathing gas regulator which is supplied with product gas containing at least 95% oxygen and which provides air dilution requires the controls which are provided on a conventional air dilution pressure demand regulator. These include selection of air dilution/100% product gas; safety pressure at low altitude (Emergency pressure); and press-to-test. In contrast, a pressure demand regulator which does not provide air dilution and in which safety pressure is present at all altitudes, and which provides pressure breathing with G and at altitude, requires only a press-to-test control. Some regulators providing the latter facilities, such as the USN chest mounted regulator type CRU-103/P, are without any manual controls. It is possible, however, to perform a press-to-test when the pressure breathing with G assembly (Combat Edge) is worn with this regulator by operating the press-to-test facility of the anti G valve. As already discussed, this procedure may cause considerable discomfort due to the high G trouser pressure involved. The advantage of providing a press-to-test facility on the breathing gas regulator, which then induces inflation of the G trousers, should be considered in any future Advanced Oxygen System. This approach is particularly relevant where the performance of a ground level inflation is part of the built-in-test of the life support system.

In breathing gas delivery systems in which there is duplication of the breathing gas regulator, an arrangement which is used in the UK, the selection of the Emergency oxygen supply should automatically select the alternative regulator. This arrangement allows the aircrew member to obtain an alternative source of supply of breathing gas and an alternative breathing gas regulator by a single simple action.

AIRCREW ORONASAL MASKS

General requirements

The major requirements of the oronasal mask for use in an Advanced Oxygen System in an agile combat aircraft are the efficient delivery of breathing gas, comfort, small size, light weight, stability especially on exposure to high $+G_z$ accelerations and minimal interference with vision and head mobility. In addition, it shall provide effective electrical transduction of speech, be easy to remove and replace, not cause dermatitis and be compatible with the wearing of aircrew corrective spectacles (2). The efficient delivery of breathing gas requires that the mask imposes the minimal resistance to breathing, maintains an effective seal to the face under all conditions of use, has minimal dead space and that the valves operate under the extremes of environmental conditions which can occur during routine flight and following escape. The requirements in these respects and the manner in which they can be met in the mask for an Advanced Oxygen System are considered in the following paragraphs. Although many aspects of the performance of an aircrew mask depend critically upon the aircrew helmet to which it is attached, aircrew helmets are not considered here.

Size, Weight and Shape

The size and weight of an aircrew mask should minimal. The centre of gravity of the mask should also be as close to the face as possible. The current ASCC standard (2) requires that the weight of the complete mask shall not exceed 400 g. The mask should also cover the minimal area of the surface of the face compatible with comfort and an efficient seal to the skin. The edge of the reflected seal of the facepiece of the mask should enclose the nose and mouth lying in the naso-labial sulcus on either side of the nose and in the sulcus below the lower lip. The advantage of the facepiece of the mask not including the point of the chin, a feature of the Royal Air Force type P and type Q series of pressure demand masks, is that it is possible to fit virtually all sizes of aircrew (male and female) with only two sizes of mask. When the facepiece of the mask includes the chin, at least four sizes of mask are required to fit 95% of the aircrew population. Adequate downward vision also requires that the profile of the mask should be as low as possible and that the suspension harness does not protrude into the visual fields (2). The internal volume of the mask should be just adequate for comfort and the respiratory dead space added by wearing the mask should be less than 200 ml (ATPD)(2). The effective dead space of existing low profile masks is generally 100 - 150 ml (ATPD). The site at which the inlet hose is connected to the mask is an important factor affecting the centre of gravity of the mask and interactions between the hose inlet connection and components of the aircrew equipment around the neck and on the front of the upper chest which interfere with downward movement of the head and hence downwards vision. Although a midline inlet connector has been used in several generations of US aircrew masks (A13A, MBU-5/P and MBU-12/P), the advantages of a side entry connection are recognised in the RAF type P/Q masks (3), and the USAF MBU-20/P mask.

The construction of the upper part of the mask must allow the wearer to occlude his/her nostrils whilst wearing aircrew gloves, in order to perform the Frenzel and/or the Valsalva manoeuvre. Approximately half the population of aircrew operating high performance low differential pressure cabin aircraft have to occlude their nostrils in order to equalise the pressure across the eardrum using one or other of these manoeuvres. This facility is provided in current aircrew masks by ensuring that the section of the mask opposite the lower part of the nostrils is flexible and that the nostrils can be occluded with the gloved thumb and finger without breaking the seal of the mask to the face.

Mask Valve System

The outlet valve of a mask to be used with a pressure demand regulator which provides safety pressure and pressure breathing must be compensated to the pressure delivered by the regulator so that gas delivered under pressure is retained in the mask. A non-return valve is fitted in the inlet port downstream of the point at which the pressure signal is taken for the compensated outlet valve. This inlet non-return valve must have a very low leakage at low differential pressures in order to ensure that the rise of pressure in the mask cavity produced by expiration is not transmitted back to the compensation chamber of the outlet valve. The diaphragm of the compensation chamber of the outlet valve should be designed so that the effective area over which the compensation pressure acts does not change with the magnitude of the compensation pressure. This feature is required in order to avoid either under- or over- compensation of the outlet valve during pressure breathing, when it will either leak or the rise of mask pressure required to open it will become excessive, respectively.

The plate of the outlet valve and the diaphragm/plate of the compensation chamber should be as light as possible to ensure low sensitivity to accelerative forces. The force exerted by the spring closing the outlet valve must be adequate to prevent the valve opening at high $+G_z$ acceleration when there is no difference of pressure between the mask cavity and the compensation chamber. This force must not, however, impose an unacceptable resistance to breathing at 1G. The effects of $+G_z$ accelerations upon the operation of the outlet valve can be minimised by mounting the valve plate in the vertical plane, although it must be recognised that changes in the position of the wearer's head may well result in the $+G_z$ acceleration acting across the plate of the outlet valve.

The compensated outlet valve should also be designed to ensure that it will not open when the compensation pressure is reduced below ambient. This requirement is met by separating the outlet valve plate from the diaphragm plate of the compensation chamber by a spring which ensures that the valve plate remains against its seat when the diaphragm/plate of the compensation chamber is retracted. This feature is required to ensure that the outlet valve is not pulled open when the mask tube pressure is reduced below ambient by an inspiration when the supply of breathing gas has failed. Whilst the design of the combined inlet and compensated outlet valve developed by Seeler (8) and employed in the US type MBU-5/P and MBU-12/P masks was ingenious and provided a small, neat assembly, it had a relatively high resistance to flow (Table 2.2 of Chapter refers), especially when it was buried within the snout of the mask. The central position of the inlet hose connection also gave a relatively high profile to this series of masks. This type of combined inlet and compensated outlet valve is not suitable for use in the mask of an Advanced Oxygen System for an agile combat aircraft.

The most satisfactory site for the inlet non-return valve in an aircrew mask is on one side of the mask, so that the valve disc (which is usually a flexible diaphragm) is placed vertically in the inlet port. The inlet valve should be protected from contamination by droplets of water or debris from the mask cavity by a guard. This feature is essential in order to maintain the performance of the inlet valve at low ambient temperatures when the temperature of the breathing gas flowing through the valve will be close to that of the environment, and may well be low enough to freeze any water present, which will interfere with the non-return function of the valve. The resistance to flow through the inlet port, non-return valve and protective guard should be minimal. A practical compromise between the bulk of the inlet connection and the resistance to flow through it is that the effective cross-sectional area of the inlet passage should be at least equivalent to that of a 16 mm diameter pipe.

The compensated outlet valve should ideally be mounted towards the bottom of the mask cavity so that fluid collecting in the mask can drain out through the valve. The requirement that the outlet valve shall operate on exposure to ambient temperatures as low as -40°C with air movement at 7.5 m sec^{-1} (2) can only be met by either trapping warm expired gas in a chamber around the valve, or electrical heating of the valve body. The usual practice is to surround the external surface of the outlet valve in a flexible snout. The outlet valve can be mounted in the bottom of the mask as in the RAF type P/Q series masks (3) or on the side of the mask (opposite to the inlet valve) as in the US MBU-20/P mask (9). The connection between the tapping in the inlet port of the mask and the compensation chamber of the outlet valve should be made by a rigid pipe (with suitable flexible couplings to allow removal and replacement of the valves).

The inlet hose carrying breathing gas from the connector on the front of the chest to the inlet port of the mask is an integral part of the mask. It may also contribute significantly to the resistance of flow of gas into the mask. The hose should be flexible and of sufficient length to allow full movement of the head without excessive bunching on looking downwards. The hose assembly must be strong enough to remain intact and functional after exposure to wind blast on ejection at high speed [the current ASCC standard(2) requires the assembly to remain intact after ejection at an indicated air speed of 600 knots (300 m sec^{-1})]. A valuable method of increasing the overall strength of a mask hose assembly is the addition of an internal restraint cord which prevents excessive elongation of the hose.

The overall resistance to breathing imposed by the complete mask assembly [inspiratory resistance measured from the free end of the mask hose (less the half coupling)] can be expressed in terms of the total swing of mask pressure during the respiratory cycle. The current ASCC standard (2) for the maximum acceptable resistance imposed by a mask is presented in Table 7.1.

Table 7.1 The maximum Acceptable Change of Pressure in the Mask Cavity during the Respiratory Cycle for a mask alone, with and without pressure breathing up to 44 inch wg (11 kPag) at all altitudes

Peak Inspiratory and Expiratory flows (litre (ATPD) min^{-1})	Maximum Change of Mask Cavity Pressure during the Respiratory Cycle (inch wg (kPag))
30	1.6 (0.4)
90	2.4 (0.6)
150	4.0 (1.0)
200	6.0 (1.5)

These values are to be met at all levels of breathing pressure from 0 to 44 inch wg (11 kPag). The resistance to breathing imposed by the current RAF type P/Q mask meets this standard (Table 2.3 of Chapter 2 refers). The resistance imposed by the USAF MBU-20/P (Combat Edge) mask is also within the limits of the ASCC standard (2) at peak flows up to at least 160 L(ATPD) min^{-1}.

An anti-suffocation valve may be required in the aircrew mask to allow the wearer to breathe ambient air when the supply of breathing gas to the inlet hose of the mask has ceased. This condition may arise due to a failure in the supply or regulation of the breathing gas or a disconnection with closure of the port in the downstream portion of the connector, for example, in the man portion of the personal equipment connector. The condition may not only arise in the cockpit but on ejection or emergency ground egress. The suction in the mask required to open the anti-suffocation

valve must be such that the valve will not open during normal operation of the breathing gas delivery system. The resistance to drawing air through the anti-suffocation valve must be sufficient to ensure that the aircrew member will always be aware that the valve is open and yet not so high that the resistance will impair respiration, especially in the unconscious individual (Chapter 5 refers). The suction required to open the anti-suffocation valve should be between 5.0 and 6.0 inch wg (1.25 - 1.5 kPag) and the pressure drop through the valve at a flow of 70 litre (ATPD) min^{-1} should not exceed 7.0 inch wg (1.75 kPag).

Seal and Suspension of the Mask

The seal of the mask to the face must be effective and comfortable. The only successful form of seal yet developed for pressure breathing masks has a reflected edge which lies against the skin. The shape of the seal should be such that when the mask is placed on the face with a pressure which is comfortable for long periods of wear, the tension in the edge of the reflected seal maintains the free edge of the seal in contact with the skin around the whole circumference of the mask. The shape, size, tension and elastic properties of the material of the seal all contribute to the effectiveness of the seal to the skin. Of very considerable importance also is the ability to adjust the position of the mask on the face and the force with which the seal is applied to the skin. It is highly desirable that the length of the suspension harness from the mask to the aircrew helmet can be adjusted with relative ease by the wearer. The turn buckles in the attachment harness of the RAF type P and Q masks provide the necessary means of adjustment very effectively.

The standard of the seal achieved with a comfortable fit should prevent the inboard leakage of air from the environment exceeding 250 ml min^{-1} when the pressure in the mask cavity is reduced by up to 4 inch wg (1 kPag) below that of the environment. It is important to recognise that the inboard leakage may be greatest at low levels of suction in the mask. The outboard leakage between the mask and the face when safety pressure is present in the mask should be minimal. The outboard leakage is not to exceed 1.8 L (ATPD) min^{-1} at mask cavity pressures between 0 and +4 inch wg (1 kPag) when measured under steady pressure conditions (2).

A mask is required to deliver breathing pressures of up to 65 - 75 mm Hg (8.7 -10.0 kPag) without significant leakage around the mask at all altitudes and at $+G_z$ accelerations up to 9G. Ideally, especially for pressure breathing with G, the mask must meet this requirement with no action from the wearer. Raising the pressure in a typical aircrew mask from 0 to 75 mm Hg (10 kPag) increases the force tending to lift the mask off the face by 9 - 10 lbf (4.1 - 4.6 kgf). This additional force has to be balanced by a similar increase in the tension around the head exerted through the mask suspension harness and the aircrew helmet. There will inevitably be some movement of these structures tending to allow the mask to move away from the face. Exposure to high $+G_z$ accelerations will accentuate these effects over certain regions of the mask seal. Finally, whilst the increase in pressure in the mouth will tend to push the cheeks closer to the edge of the mask, this movement can make the seal less effective in some regions. This is particularly so if the centre of pressure and the line of suspension of the mask do not coincide, so that the increase in pressure rotates the mask, tending to lift it off either the nose or the chin. Should there be a leak from the mask, it is preferable that the leak is from the lower part of the mask and especially that no gas is directed into the eyes. The outboard leak from a mask during pressure breathing should not exceed 6 L (ATPD) min^{-1} at a breathing pressure of 30 mm Hg (4 kPag) and 15 L (ATPD) min^{-1} at a breathing pressure of 82.5 mm Hg (11 kPag) when measured under steady pressure conditions (2).

It is difficult to produce a mask which in practice will seal high breathing pressures without some mechanical adjustment of the suspension of the mask on the head. For many years, the only effective method of providing a comfortable fit during routine wear, and a good seal at high breathing pressures, was the toggle suspension harness of the type P/Q series of masks (5). Rotation of the toggle of the harness shortens the length of the suspension system between the mask and aircrew helmet to provide a good seal at breathing pressures up to at least 70-75 mm Hg (9.3 - 10 kPag). To date, two approaches have been partially successful in providing automatic tensioning of the suspension system of a mask during pressure breathing. The most widely used method is to fit a bladder over the back of the head between the suspension system of the helmet and the head of the wearer. The bladder, whose area is somewhat greater than that of the face covered by the mask, is inflated with breathing gas to the breathing pressure by a pneumatic connection between the bladder and the inlet hose of the mask immediately upstream of the inlet non-return valve. This mask tensioning system is embodied in the USAF Combat Edge pressure breathing with G assembly and in French pressure breathing with G assembly for the Rafale aircraft. It has also been in use for several decades in Russian pressure breathing mask systems. An alternative method, which has been applied to the RAF type P/Q series of mask in which the silicone facepiece is supported by a rigid exoskeleton, is to place a bladder between the facepiece and the exoskeleton. Again, the bladder is inflated to breathing pressure through a tapping into the inlet port of the mask. Neither of these bladder systems has proved to be fully effective when used by a variety of aircrew.

SUMMARY

The breathing gas delivery system of an Advanced Oxygen System for an agile combat aircraft should be as simple and reliable as possible commensurate with providing the facilities which are required and with meeting the relevant physiological standards. The latter are well summarised in the current ASCC documents on aircrew breathing systems (1) and aircrew masks (2). Whilst the pressure demand regulator of the delivery system can be mounted in any of the conventional sites in a side console, on the ejection seat and on the torso, the relative advantages of these sites favour mounting on the ejection seat in conjunction with a personal equipment connector. The major exception to this conclusion is in ship-borne aircraft where survival following ejection over the sea requires an underwater breathing facility. This can best be provided by torso mounting of the regulator. Consideration should be given to duplicating the pressure demand regulator which is most effectively done when the pressure demand regulator package is mounted on the ejection seat.

Wherever the pressure demand regulator is sited, the regulator should provide breathing gas on demand at the high

flows required to minimise resistance to breathing over the whole range of regulator inlet pressures which may occur in the Advanced Oxygen System. It should provide the breathing gas with safety pressure from ground level, pressure breathing with G, pressure breathing at altitudes above 40,000 feet and pressure breathing on "press-to-test" on the ground. A compensated dump valve should be included at the outlet of the regulator to prevent excessive rises of mask tube pressure. Panel, seat and torso mounted pressure demand regulators, which meet these requirements to varying degrees, have been developed and are being introduced into service with the first generation of MSOC systems. Initial operational experience suggests that they are fully acceptable in so far as they meet the requirements described in this Chapter. There remain some areas in which the performance of these regulators should be improved, especially the resistance to breathing imposed at low regulator inlet pressures and the performance of the dump valve on full flow failure of the demand valve and rapid decompression. With minor development, this generation of regulators will be suitable for use in Advanced Oxygen Systems for future agile combat aircraft. In considering the integration of the life support systems, consideration should be given to combining into a single package, the breathing gas pressure demand regulator and the anti-G valve, and mounting this package on the ejection seat, perhaps integrated into a personal equipment connector. Wherever the regulator is mounted, every effort should be made to minimise the resistance to flow through the breathing gas delivery pipework from the outlet of the regulator to the inlet port of the mask.

The special features required of an aircrew mask for an Advanced Oxygen System for an agile combat aircraft are low weight, low profile, low resistance to breathing, and an efficient seal to the face under all conditions of use whilst being comfortable to wear for at least 8 hours. Low resistance to breathing and a low profile are best provided by separate inlet non-return and compensated outlet valves which are mounted with the valve plates as vertical as possible when the head is in the erect position. Each of the valves should present minimal resistance to gas flow under all environmental conditions, including high $+G_z$ accelerations, high altitude and low temperatures, with safety pressure and during pressure breathing. Whilst inlet non-return valves which meet all these criteria are available, improvements are required to the design of many compensated outlet valves to provide the required performance, especially during pressure breathing with G. The resistance to flow through the inlet hose of the mask must be minimised whilst ensuring that the flexibility and strength of the hose and its attachments are adequate.

The sealing properties of all advanced aircrew masks require improvement, particularly with respect to the maintenance of a good seal on exposure to high breathing pressures at high $+G_z$ accelerations and at high altitude. Furthermore, a major improvement is required to the automatic provision of a good seal to the face under these conditions. The present generation of masks only provide an acceptable seal to the face when the tension in the mask suspension system is increased manually before, or at, the beginning of the exposure to $+G_z$ accelerations. The deficiency of present masks can probably only be corrected by a thorough re-examination of the design of the seal itself and a major change to the design of the mask suspension system.

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Chapter 8

CURRENT MOLECULAR SIEVE OXYGEN GENERATION SYSTEMS

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Kenneth G. Ikels, Richard M. Harding, and Donald J. Harris

INTRODUCTION

This chapter describes molecular sieve oxygen generating systems (MSOGS) that have been developed and flight tested, and, in a few cases, transitioned to operational military aircraft. The aircraft systems, for the most part, are listed in chronological order of development.

AV-8A OXYGEN ENRICHED AIR SYSTEM (OEAS)

In the early 1970s, the U. S. Navy initiated development of onboard oxygen generation technology with the dual objective of reducing the logistics burden of liquid oxygen supply, as well as the incidence of oxygen mishaps on aircraft carriers. A third objective, namely conducting flight operations from non-aircraft carrier ships evolved from the concurrent development of very short takeoff and landing (VSTOL) aircraft such as the AV-8 Harrier. In the mid-1970s, the OBOGS program narrowed to molecular sieve technology, when laboratory testing of MSOGS confirmed the feasibility of producing a breathing gas containing 93-95% oxygen (see Chapter 3). Following the successful flight trials of a two bed molecular sieve oxygen concentrator developed by Litton Instruments and Life Support Division in an EA-6B aircraft, the US Navy sponsored continued development of this oxygen generating system by conducting an extended operational trial and evaluation in six AV-8A Harrier aircraft (14).

The Oxygen Enriched Air System (OEAS) developed by Litton was designed to replace the standard LOX system in the AV-8A aircraft with a minimum of modification to the airframe (22). The system consisted of three major components: molecular sieve oxygen concentrator, breathing gas regulator, and performance monitor (oxygen sensor). Figure 8.1 shows a simplified flow schematic of the system.

Control and Conditioning of Process Air

The OEAS was supplied with 8th stage engine bleed air, controlled by a 28 VDC motor-driven butterfly valve. The hot bleed air (176 °C to 510 °C) was routed through an airframe mounted heat exchanger which reduced the temperature of the air to between -7 and 88 °C depending on geographic location and altitude. The cooled bleed air passed to an airframe mounted pressure regulator which reduced the pressure to 28 lbf in^{-2} gauge (193 kPag) before admission to the concentrator. Bleed air flow to the concentrator was limited by the airframe regulator to a range from 0.7 to 0.9 lb (0.32 - 0.4 kg) min^{-1} depending on aircraft altitude. The internal diameter of the pipework between the engine and the oxygen concentrator was 0.57 in. (14.5 mm).

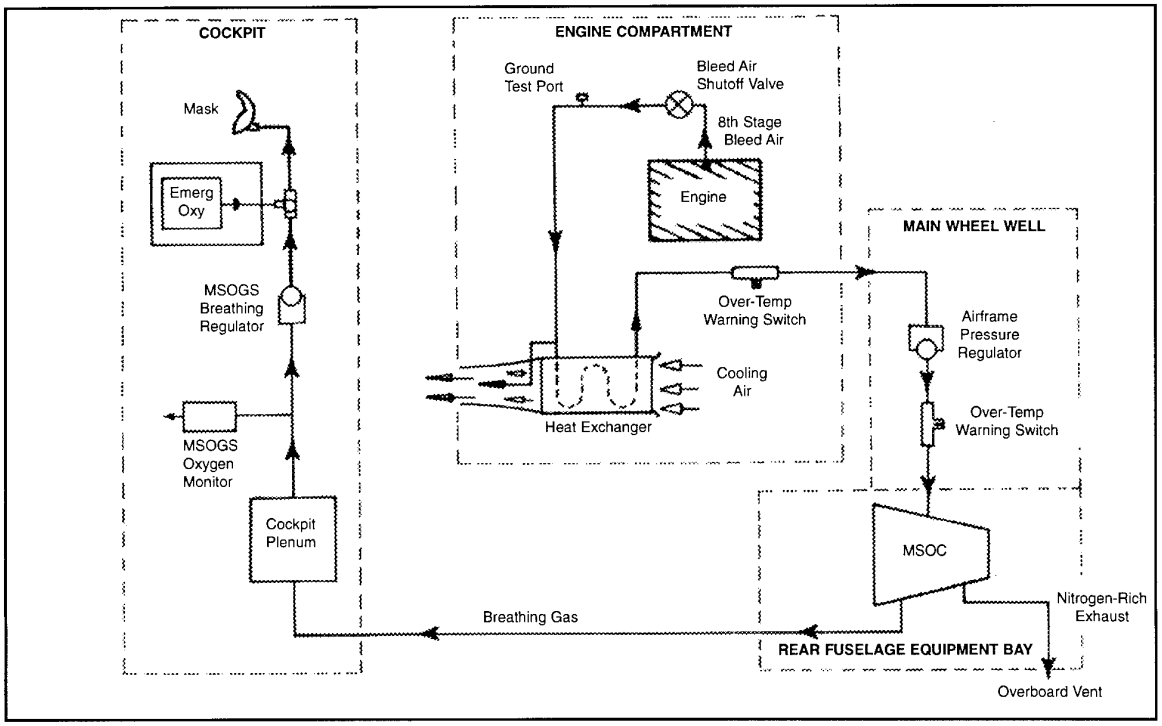

Fig. 8.1 Simplifed flow schematic for AV-8A oxygen enriched air system (OEAS).

Oxygen Concentrator

The molecular sieve oxygen concentrator (Figure 8.6) which was mounted in the rear fuselage equipment bay was designed to replace the standard 5 liter LOX converter. It had dimensions of 33 cm wide by 26 cm high by 27 cm deep. The concentrator weighed 18.6 kg (41 lb) and consisted of: (a) two beds, each containing approximately 2.5 kg of molecular sieve type 5A MG, (b) air heater,(c) air filter, (d) pressure reducer, and (e) control valve.

The concentrator molecular sieve beds were designed with annular geometry. The outer annulus of each bed contained approximately 2 kg of molecular sieve while the inner core contained approximately 0.5 kg of molecular sieve. At the bottom of the bed was a small (6 mm) dead space covering the entire diameter of the bed. The incoming air was directed downward through the outer portion of the bed, upward through the inner annulus, and out through the product plenum.

Two resistance heaters surrounding the inlet air plenum maintained the temperature of the air entering the beds at 40-46 °C to ensure adequate performance of the concentrator at low ambient temperatures. The temperature sensor for the two resistance heaters was located at the outlet of the plenum. The maximum power consumption of the air heater was 616 watts (10.6 amps for each heater at 29 VDC).

A coalescing filter mounted downstream of the inlet plenum removed particulate and aerosols. The filter element had a capture efficiency of 99.99% against 0.1 micron particles, and was designed to prevent carryover of coalesced liquid. The coalesced liquid drained from the outside of the filter tube and out through a bleed port located in the bottom of the filter housing.

Inlet air flowing from the filter passed to a pressure regulator/reducer which limited air consumption and prevented excessive pressure in the beds, plenum, pipework, and breathing gas regulator. The reducer delivered air to the beds of the concentrator at the pressure at which it was supplied when the latter was less than 25 lbf in^{-2} gauge (172 kPag). When the bleed air pressure exceeded this value, the pressure delivered by the reducer increased in a linear manner to 67 lbf in^{-2} gauge (462 kPag) at a supply pressure of 250 lbf in^{-2} gauge (1,720 kPag). The flow of air to the beds was controlled by a two port valve which rotated continuously in one direction. While one port of the rotary valve was conducting air to one bed, the second port connected the other bed to the exhaust outlet through which the latter bed was depressurized and the purge gas flowed to ambient. Halfway through the rotation, the connections of the inlet and outlet ports were reversed thus alternating the pressurization and depressurization phases of the two beds. The motor-gearhead drove the rotary valve at a constant speed of 6 rpm, which produced one complete cycle every 10 seconds. The drive motor operated from a nominal 400 cycle power provided by an invertor which operated with 18-29 VDC.

The product gas from the adsorbing molecular sieve bed passed through a check valve into the outlet plenum from which it flowed through an 0.5 μ filter to the breathing gas regulator. Most of this product gas flowed through the purge orifice into the downstream end of the desorbing molecular sieve bed. This gas purged the bed and vented the nitrogen and other contaminant gases to ambient via the control valve and exhaust port. The existing oxygen delivery line [internal diameter 0.313 in (7.9 mm)] was utilized to carry the product gas from the concentrator to the cockpit.

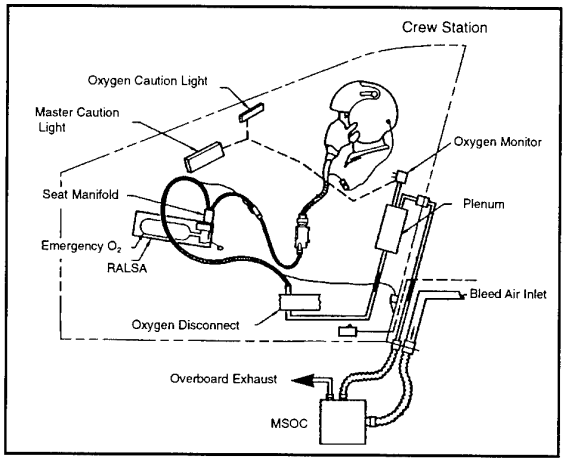

Fig. 8.2 Crew station oxygen equipment installation schematic for AV-8A OEAS.

Cockpit Plenum

The oxygen delivery line carrying product gas was connected to a 1.6 L plenum chamber which was mounted on the rear bulkhead of the cockpit. This plenum acted as a momentary gas reservoir to support high volume inspiratory flows, and as a heat sink to maintain temperature stability.

OEAS Performance Monitor

The OEAS Performance Monitor (polarographic type) measured the PO_2 of the product gas and provided a warning signal in the event that the PO_2 fell below 220 ± 10 mm Hg. The performance monitor was mounted on the rear bulkhead of the cabin and received a bleed of product gas (nominally 1 L min^{-1}) from immediately downstream of the cockpit plenum. This sample of product gas passed through a metering orifice into a chamber where it flowed over the surface of the PO_2 sensor. The product gas sample then flowed freely into the pressure cabin so that the absolute pressure of the product gas around the sensor was that in the cabin. The PO_2 was measured by a replaceable polarographic sensor comprising a gold cathode and a silver anode immersed in an electrolyte gel. The sensor tip was covered by a Teflon membrane permeable to oxygen. The current which flowed between the electrodes when a polarizing voltage was applied was proportional to the PO_2 of the gas flowing over the tip of the sensor. In order to avoid spurious PO_2 warnings when the cabin altitude exceeded 28,000 feet, an aneroid operated valve restricted the flow of product gas from the PO_2 chamber to the pressure cabin above this altitude, so that the absolute pressure in the PO_2 sensor chamber was held at 28,000 feet. The Performance Monitor was fitted with an electric heater which prevented the temperature of the sensor chamber falling below +4 °C as the PO_2 sensor would not operate effectively at temperatures below 0 °C. The Performance Monitor was fitted with a Built-In-Test facility whereby air could be drawn over the PO_2 sensor at

ground level so that the monitor activated the low PO_2 warning light.

Cockpit Pipework and Connectors

Several arrangements of the breathing gas regulator and connecting pipework were used during the development and technical evaluation of the system in the AV-8A aircraft. The final arrangement adopted for the operational evaluation of the system mounted the breathing gas regulator on the pilot's chest and carried the product gas from the cockpit plenum through the pilot's services panel on the left hand console, and a quick disconnect to the emergency oxygen manifold in the Restraint and Life Support Assembly (RALSA)of the ejection seat. Product gas was carried from this manifold by a flexible hose and connector to the chest mounted regulator. Figure 8.2 is a schematic of the AV-8A crew station oxygen equipment installation.

Backup Oxygen System

A 200 liter (STP) emergency oxygen supply was located in the RALSA to provide oxygen during high altitude escape, and underwater survival. This emergency system also served as the backup system in the event of OEAS failure or loss of engine bleed air. Activation of the emergency system provided 1800 lbf in^{-2} (12,400 kPag) to the RALSA manifold slider valve which caused it to close over the OEAS port, thus routing emergency oxygen to the pilot.

Controls and Displays

The OEAS ON-OFF switch was located on the right hand console. In the ON position this switch opened the motor driven air valve and allowed engine bleed air to flow to the concentrator. This switch also activated power to the concentrator rotary valve motor.

Low oxygen partial pressure or excessive process air temperature (149 °C sensed at the bleed heat exchanger or 121 °C sensed at the airframe pressure regulator) illuminated the aircraft master caution lights (amber) and the oxygen warning and temperature warning lights (red).

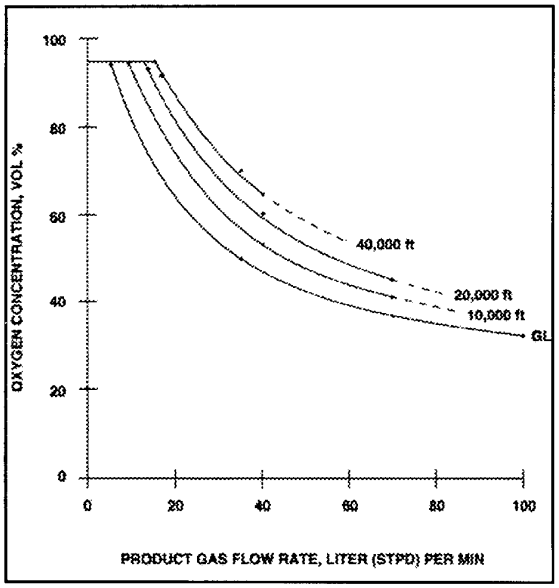

Fig. 8.3 Performance of the AV-8A molecular sieve oxygen concentrator, concentration of oxygen as a function of product flow; parameter is simulated flight altitude.

Breathing Gas Regulator

The standard US Navy chest mounted oxygen regulator was unsuitable for use with the OEAS because its minimum inlet pressure for satisfactory performance was 40 lbf in^{-2} (276 kPag), whereas the minimum pressure at which product gas could be delivered to the regulator by the OEAS was as low as 5 lbf in^{-2} (34 kPag). Also, the magnitude of the pressure breathing which the standard regulator delivered at altitudes above 40,000 feet was inadequate to maintain an acceptable alveolar PO_2 with product gas containing only 93-95 % oxygen. The modified regulator developed for the OEAS was a pressure demand unit which provided safety pressure at all altitudes up to 40,000 feet, and pressure breathing between 40,000 and 50,000 feet. It had a balanced demand valve and a relatively large breathing diaphragm. The maximum inlet pressure to the regulator in the OEAS was approximately 22 lbf in^{-2} gauge (152 kPag). At this pressure, the regulator delivered a maximum flow of 160 L (ATP) min^{-1}.

Performance of OEAS

The basic OEAS components were environmentally tested at the Naval Air Development Center and the system was manrated at the Armstrong Laboratory (Figure 8.3). The OEAS was installed in six AV-8A aircraft for fleet evaluation. Initially deployment took place aboard the LHA USS Tarawa in October, 1980. Operational testing continued through 1984 with over 5000 flight hours logged in deployments which ranged from South Pacific to North Atlantic environments. The outstanding success of the AV-8A program led directly to the full scale development and installation of OEAS in the AV-8B, as described below.

AV-8B SUPER HARRIER OXYGEN ENRICHED AIR SYSTEM

Based on the proven success in the AV-8A aircraft, the Oxygen Enriched Air System was incorporated into the base line design for the AV-8B aircraft utilizing most of the same components. The AV-8B aircraft uses the same breathing regulator, concentrator, performance monitor, bleed air control valve, heat exchanger, backup oxygen system, and the basic hose routing in the cockpit as the AV-8A aircraft. Changes in the AV-8B airframe design required relocation of some components, and other changes were made to improve system performance and maintainability. Figure 8.4 shows the general arrangement of the AV-8B crew station oxygen equipment installation.

The aircraft mounted pressure regulator employed in the AV-8A OEAS was removed in the AV-8B design to reduce pressure drop and smooth bleed air flow to the oxygen concentrator. As a safety precaution, an 80 lbf in^{-2} gauge (550 kPag) pressure relief valve was added to the oxygen pipework, in addition to the pressure relief valve already located in the concentrator.

Additionally, the concentrator was moved from a rear mounted location in the AV-8A to a location under the cock-

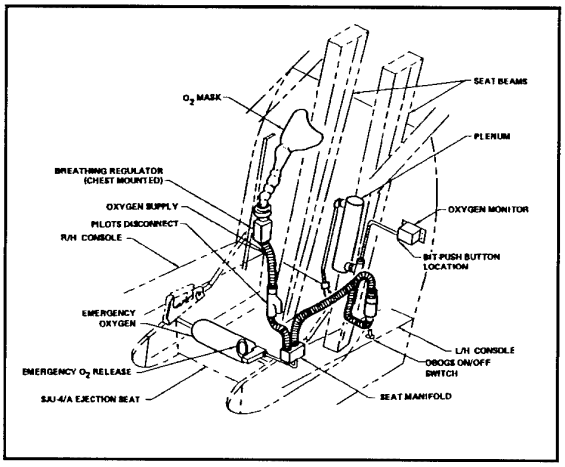

Fig. 8.4 Crew station oxygen equipment installation schematic for the AV-8B aircraft.

pit floor of the AV-8B. This allowed shorter gas lines to reduce pressure drop through the system, which ultimately improved breathing performance at the low engine bleed air pressures encountered at idle and low engine power setting. Breathing performance at idle condition was increased from an average flow rate of 18 to 22 L min^{-1}. The reduction in system pressure loss by pipework design and removal of the airframe pressure regulator improved the peak inhalation flow capacity from 160 to 250 L (ATP) min^{-1}, and the minute volume capacity from 52 to 80 L (ATP) min^{-1} at low altitude flight conditions.

Since the OEAS was part of the basic design of the AV-8B aircraft, the controls and displays were simplified into standard function grouping. In the AV-8B, the OEAS performance monitor was located on the cockpit aft pressure bulkhead. The plenum remained behind the ejection seat mounted to the bulkhead but, to simplify manufacturing, the basic design configuration was changed from six tubes manifolded together in the AV-8A to one singular cylinder arrangement in the AV-8B. The AV-8B pipework and hose connections in the cockpit are almost identical to the AV-8A.

The AV-8B also used the RALSA emergency oxygen system for backup. However, an additional lever was added to allow the pilot to deselect the emergency oxygen before it was exhausted. This allowed the pilot to use the backup system for a short period of time during an engine out period, and then shut off the backup oxygen supply and reselect the OEAS after engine restart.

In the early 1980s, the full scale development and limited production AV-8B and TAV-8B (2-seat training version) aircraft were equipped with molecular sieve oxygen generation systems. In November 1984, approval for full production was granted for MSOGS in the T/AV-8B aircraft, and by 1995, over 160 T/AV-8B aircraft had been built. The MSOGS has received wide acceptance in fleet use and no unique problems have developed. As a result of this success, the U. S. Navy has initiated development of MSOGS for virtually all carrier base aircraft, including the A/F-18 Hornet, F-14D Tomcat, and V-22 Osprey, as well as for the T-45 trainer.

HARRIER GR MK 5/7 AIRCRAFT MOLECULAR SIEVE OXYGEN GENERATING SYSTEM

The Harrier GR Mk 5/7 is the Royal Air Force version of the AV-8B and is manufactured jointly by McDonnell Douglas Corporation and British Aerospace. The decision to fit a UK ejection seat to the RAF version of the aircraft made it possible to replace the chest mounted pressure demand regulator and the RALSA-mounted emergency oxygen supply fitted to the AV-8B by a UK designed and manufactured system. The opportunity was also taken to introduce a facility whereby the concentration of oxygen in the product gas was prevented from rising above 60% at cabin altitudes up to 15,000 feet thereby avoiding acceleration-induced atelectasis and delayed otitic barotrauma.

Installation

The Harrier GR Mk 5/7 employs the identical Molecular Sieve Oxygen Concentrator that is fitted to the AV-8B (Figure 8.6). The concentrator is however built in the UK by Negretti Aviation Ltd (under license from Litton). The system supplying air to the concentrator and carrying product gas from the concentrator to the plenum mounted on the rear bulkhead of the pressure cabin is also identical to the arrangement in the AV-8B. Product gas passes from the plenum to a mixture controller and thence through a flexible hose to the seat mounted components of the system. The latter comprise the emergency oxygen supply, a combined reducing and selector valve, a flow sensor, a personal equipment connector and a duplex demand oxygen regulator. The system is shown schematically in Figure 8.5.

Mixture Controller

The concentration of oxygen in the product gas is controlled by varying the flow of gas from the concentrator, the concentration of oxygen falling as the flow is increased. The additional flow is demanded by the Mixture Controller which contains a dump valve through which product gas flows to the cabin. The opening and closing of the dump valve, which passes a flow of 70 ± 5 L (NTPD) min^{-1} at a product gas pressure of 30 lbf in^{-2} g (207 kPag) is controlled by a fluidic oxygen sensor which monitors the PO_2 of the

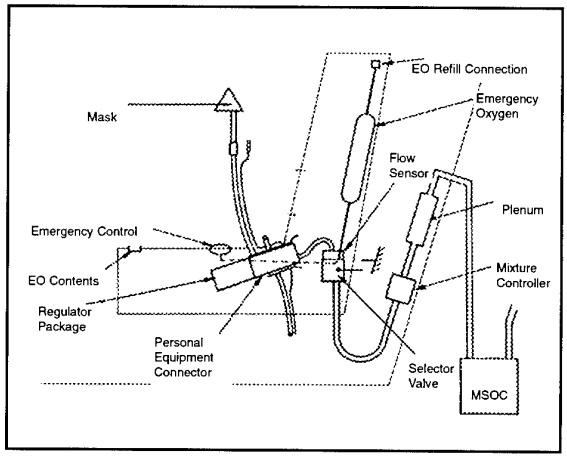

Fig. 8.5 A diagram of the installation of MSOGS in the RAF Harrier GR Mk 5/7 aircraft.

product gas. The dump valve is also closed when the pressure of the product gas falls below 5 lbf in^{-2} g (34 kPag) or the cabin altitude exceeds 21,000 feet. The Mixture Controller also contains a second fluidic oxygen sensor which switches when the PO_2 of the product gas falls below 180 ± 20 mm Hg (24 ± 2.7 kPa), when its operation illuminates a red warning on the control warning display.

Selector Valve and Emergency Oxygen

The product gas is carried through a seat-to-airframe disconnect to the Selector Valve whereby either product gas or emergency oxygen is supplied to the demand regulator. The emergency oxygen supply comprises a bottle mounted in the back of the ejection seat which is charged to 1,800 lbf in^{-2} g (12,400 kPag) when it contains 200 litre (NTPD) of gas. There is a remote recharging point. The outlet of the bottle is connected to the reducing valve within the Selector Valve which reduces the pressure to 30 ± 10 lbf in^{-2} g (207 ± 69 kPag). The emergency oxygen supply is selected automatically when the cabin altitude exceeds 23,000 feet and on ejection. It can also be selected by the pilot operating a seat mounted control. The latter is reversible so that product gas may be reselected. Selection of the emergency oxygen supply illuminates an amber caution light. The contents of the emergency oxygen bottle are displayed on a gauge mounted on the front of the seat pan where the pilot can see it in flight. Selection of the emergency oxygen supply opens a small orifice whereby product gas can bleed to the cabin. This provision ensures that the concentration of oxygen in the product gas is appropriate to the cabin altitude should the pilot reselect product gas.

A flow sensor between the Selector Valve and the Demand Regulator Package operates a magnetic indicator which provides a visual display of the flow of gas through the system.

Regulator Package

The product gas is carried from the Selector Valve and flow sensor through the personal equipment connector to the dual-regulator package which is attached to the front face of the personal equipment connector. The type 600 regulator package consists of two demand regulators (main and standby) both of which provide safety pressure but no pressure breathing, which is not required. The main regulator, which is used routinely, provides a nominal safety pressure of 1.5 inch water gauge (0.38 kPag). The nominal safety pressure of the standby regulator is higher at 3.0 inch water gauge (0.75 kPag), a facility which is employed to ventilate the hood space of the Aircrew Respirator NBC No: 5, following a failure of the blown filtered air supply. A compensated dump valve at the outlet of the regulator prevents excessive rise of outlet pressure. A manual control allows the pilot to select either the main or standby regulator. The standby regulator is also selected when the manual emergency oxygen control is operated. The outlet of the regulator package delivers breathing gas through the personal equipment connector to the mask hose.

Performance Testing

A full evaluation of the complete system was performed by the RAF Institute of Aviation Medicine during development. The resistance to breathing exhibited by the complete system fully met the requirements of ASCC Standard (2) and the concentration of oxygen in the product gas was higher than that required to maintain an alveolar PO_2 of 103 mm Hg (13.7 kPa) but did not exceed 60% at cabin altitudes below 15,000 feet. 100% oxygen (from the emergency oxygen supply) was delivered to the mask cavity rapidly on sudden decompression to altitudes above 23,000 feet. A representative system was installed in the RAF IAM's Hunter T Mk 7 and a full flight test programme confirmed the satisfactory performance of the MSOGS throughout the flight envelope.

Extensive operational experience of the Harrier GR Mk 5/7 has provided strong evidence of the high reliability of the molecular sieve oxygen concentrator system fitted to the aircraft. The concentrator, the mixture controller and its fluidic sensors, and the regulator have performed fully satisfactorily without any significant malfunctions.

U. S. ARMY JU-21G (FIXED WING TURBOPROP) AND JUH-1H (TURBINE POWER HELICOPTER) MOLECULAR SIEVE OXYGEN GENERATING SYSTEMS

In the early 1980s, the U. S. Army Aeromedical Research Laboratory procured three different molecular sieve oxygen generating units for flight test in US Army aircraft. The three units were developed by Litton, Airesearch, and Essex, respectively. All three units were flight tested in both a fixed and rotary wing aircraft (4,5,21). The fixed wing aircraft was a JU-21G "Ute", a two-pilot, 6-passenger twin-engine turboprop. The rotary wing aircraft was a JUH-lH turbine powered helicopter.

Litton Unit

The Litton unit was essentially identical to the concentrator deployed on the AV-8A aircraft, which is described above.

Airesearch Oxygen Generating Unit (OGU)

The Airesearch concentrator (Figure 8.6) was nominally two-man capacity and had dimensions of 30.6 cm wide x

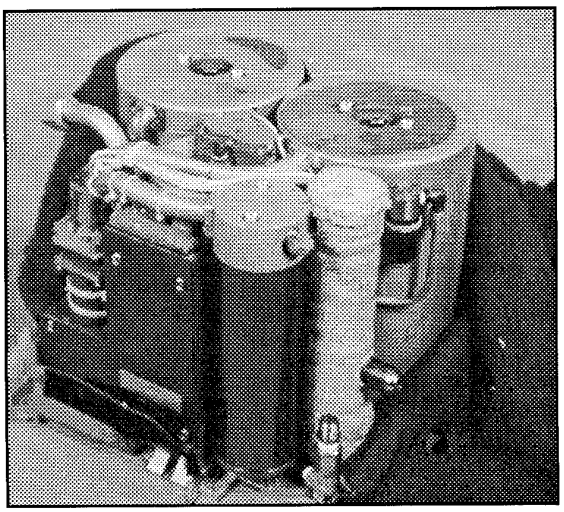

Fig. 8.6 Litton molecular sieve oxygen concentrator - used in T/AV-8A, T/AV-8B and tested by US Army for use in unpressurized aircraft.

24.7 cm high x 27.5 cm deep. It weighed 15.9 kg (35 lb). The concentrator consisted of two sorbent beds housed in aluminum castings, a rotary inlet valve driven by a 28 VDC motor, air filter, regulator/shutoff valve relief valve and check valves.

The beds of the concentrator were cylindrical and "U" shaped. Each bed was filled with 4.6 kg (10.2 lb) of molecular sieve type 5A (Medical Grade), and was spring loaded with a small dead space at each end of the bed. Flow of process air traversed the length of the bed in a single pass. Bleed air entered the OGU through a particulate filter (10 μ nominal pore size), a shutoff valve (to prevent diffusion of moisture into the molecular sieve beds during periods of non-operation), and an air pressure regulator, which adjusted the bleed air pressure to 30±5 lbf in^{-2} gauge (207±34 kPag). From the regulator, the bleed air passed through a rotary inlet valve which directed the flow into the producing (or sorbing) bed. The spacing of the channels in the rotary inlet air valve was designed to cause an overlap of approximately 0.5 seconds during the changeover from foreflush to backflush; i.e., process air was admitted to the inlet of the backflushing bed before the foreflush was terminated. This procedure served to shorten the pressurization time and minimize the pressure swing in the product gas line. This, in turn, negated the need for a plenum to balance the pressure pulse at bed changeover.

Laboratory evaluation of the OGU concentrator was conducted at the Armstrong Laboratory and measured product oxygen concentration as a function of steady-state product flow (9). The effect of air supply pressure was also measured at simulated pressure altitudes of 8,000, 16,000, and 25,000 feet.

The Airesearch concentrator was flight tested in the static mode in both fixed and rotary wing aircraft at the US Army Aeromedical Research Laboratory, Fort Rucker AL. In the flight tests only the concentrator of the OGU was evaluated with the use of a specially constructed test stand mounted in the aircraft (5). The test stand contained an oxygen monitor and flowmeter for setting product gas demand. Five separate flights were flown at different altitudes in each of the aircraft. The oxygen concentration of product gas was recorded at flows of 15, 25, 35, and 70 L min^{-1}. Results of the flight tests indicated that the oxygen production of the concentrator met or exceeded the oxygen concentration requirements of the USAF diluter-demand regulator specification (27) at all flows and altitudes (Figure 8.8).

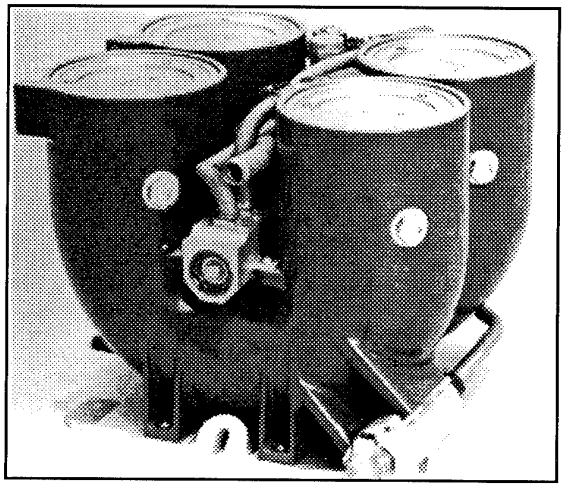

Fig. 8.7 Airesearch oxygen generating unit (OGU) tested by US Army for use in unpressurized aircraft.

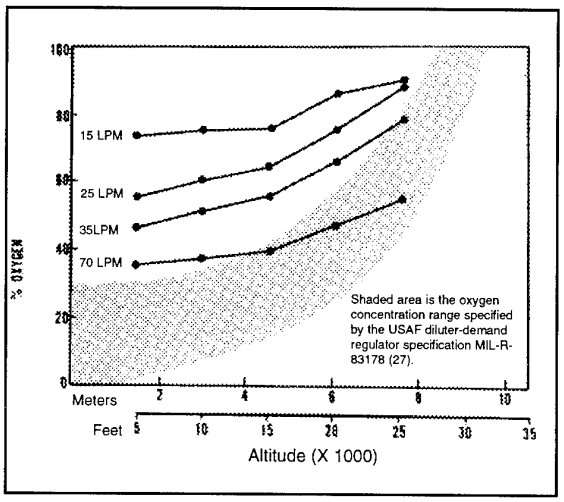

Fig 8.8 Flight test performance of the Airesearch oxygen generating unit (OGU). [Data taken from Chaffin et al (4)].

Essex Concentrator Unit

Essex Cryogenics of Missouri, Inc. is a major producer of aircraft liquid oxygen converters for the USAF. In the late 1970s, Essex developed a prototype three-bed molecular sieve oxygen concentrator which they named OBOES, Onboard Oxygen Enrichment System. The OBOES consisted of three cylindrical zeolite beds stacked in a triangular configuration with their long axes horizontal, mounted on a standard liquid oxygen converter wedge plate (Figure 8.9). Connecting tubing and an end plate supported the structure, which housed a pressure reducing valve, DC motor, rotating feed/vent valve, and a small product gas plenum in its core.

The OBOES measured 38 x 32 x 31 cm, weighed 17 kg, and consumed about 30 watts of 28 volt DC power. OBOES operated on a relatively rapid adsorption-desorption cycle. The inlet air rotary valve turned at 25 revolutions min^{-1}. The concentrator was evaluated in the Armstrong Laboratory simulating altitude, temperature, supply air pressure, and product gas flow demand that might be encountered in operational use (26). Altitude test points ranged from ground level to 50,000 feet with the cabin both pressurized and depressurized. Thermal exposures were conducted at 130, 65, -40, and -60 °C. Input air pressure ranged from 10 to 60 lbf in^{-2} gauge (69-414 kPag), and breathing gas demand flows from 10 to 100 L (ATPD) min^{-1}. Performance of the OBOES was comparable to other molecular sieve oxygen generation units of a similar size. Product gas oxygen enrichment generally increased with increasing inlet air pressure, higher altitude, or lower product demand flow. At ground level, maximal oxygen concentration (product gas more than 92 percent oxygen) was achieved with inlet pressure over 30 lbf in^{-2} g (207 kPag) and product flows under 50 L (ATPD) min^{-1}. At 40,000 feet (cabin decompressed), 92 percent oxygen could be generated with 20 lbf in^{-2} g (138

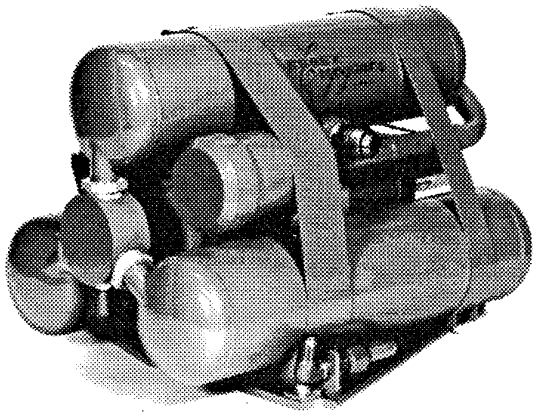

Fig 8.9 Essex Cryogenics Onboard Oxygen Enrichment System (OEAS).

kPag) or greater inlet pressure and flows up to 100 L (ATPD) min^{-1}. Because the zeolite beds were packed very tightly in this concentrator, pressure drop through the unit was high. More than 30 lbf in^{-2} g (207 kPag) inlet pressure was required to provide 10 lbf in^{-2} g (69 kPag) pressure at the concentrator outlet. High or low environmental temperatures depressed oxygen output by 10-15 percent under the conditions tested, but recovery was rapid upon return to normal temperature (21 °C).

NORMALAIR-GARRETT LTD ADVANCED OXYGEN SYSTEM MK 2

Development of an aircraft advanced oxygen system employing molecular sieve technology was commenced in the United Kingdom by Normalair-Garrett Ltd (NGL) in 1975. NGL elected to use three beds of molecular sieve to ensure an uninterrupted flow of product gas. A three bed concentrator which employed two cycle times, and a pressure demand regulator operating at low inlet pressures, was incorporated into the Advanced Oxygen System (AOS) Mk 1 which was assessed by the RAF Insitute of Aviation Medicine (IAM) in 1982. The cycle time of the concentrator was controlled by cabin altitude. Following the satisfactory completion of laboratory tests, the AOS Mk 1 was installed in the RAF IAM's Hunter T Mk 7 aircraft. The flight test programme performed in 1983, which included aerobatics and simulated air combat up to +6Gz, demonstrated the very satisfactory performance of the system (3). NGL subsequently introduced closed loop control of the oxygen concentrator employing a fluidic PO_2 sensor to select the cycle speed. This concentrator was embodied in the AOS Mk 2 which was assessed in the laboratory and then installed in the RAF IAM Hunter T Mk 7 aircraft and a flight test programme conducted in 1984/85.

System Description

The AOS Mk 2 as installed in the RAF IAM Hunter aircraft comprised air shut off valve, oxygen concentrator, fluidic PO_2 sensors, backup oxygen supply with manual and automatic selection, low inlet pressure demand regulator, low pressure delivery hose, emergency and bale-out oxygen, and type P/Q mask. A schematic of the installation is presented in Figure 8.10. The air supply which was obtained downstream of the pre-cooler of the environmental control system maintained the pressure at the inlet to the oxygen concentrator at 25-28 lbf in^{-2} gauge (172-193 kPag) during most phases of flight but at engine idle, the inlet pressure fell to 5-8 lbf in^{-2} gauge (35-55 kPag).

Oxygen Concentrator

The oxygen concentrator which was designed to provide breathing gas for two crew members, consisted of three separate cylindrical beds each containing 3.2 kg of molecular sieve type 13X, mounted on a baseplate which contained the inlet, vent and product valves and connecting passages. An inlet pressure regulator and filter, and an electronic timer unit were also mounted on the baseplate (Figure 8.11). The oxygen concentrator weighed 20.6 kg and its overall dimensions were 31.0 cm x 29.9 cm x 33.0 cm.

The inlet pressure regulator limited the pressure at which air was supplied to the beds to 40 lbf in^{-2} gauge (276 kPag). Each bed had its own pneumatic diaphragm type inlet and vent valves. The product gas flowing from the bed passed through a non-return valve to the common product gas outlet of the concentrator. The front end of each bed was connected through its vent valve to a common vent. An orifice fitted to each bed allowed product gas to back purge the bed when its vent valve was open. The inlet and vent valves of each bed were controlled by a single solenoid operated pneumatic valve. The timing of the opening and closing of the inlet and vent valves of the three beds (Figure 8.12) was such that the opening of the air inlet valves of any two beds overlapped, so that at no time was the flow of air into, or of product gas from, the concentrator interrupted. The electronic timer operated at two cycle times, 9.6 and 32.0 sec. The cycle speed was controlled by the output of a fluidic oxygen sensor which sampled product gas and switched at a nominal PO_2 of 240 mm Hg (32 kPa).

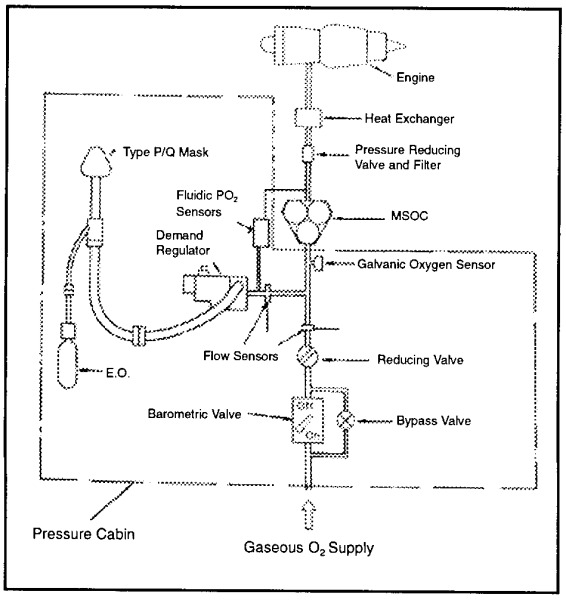

Fig. 8.10 A schematic diagram of the installation of the NGL Advanced Oxygen System Mk 2 in the RAF IAM Hunter T Mk 7 aircraft.

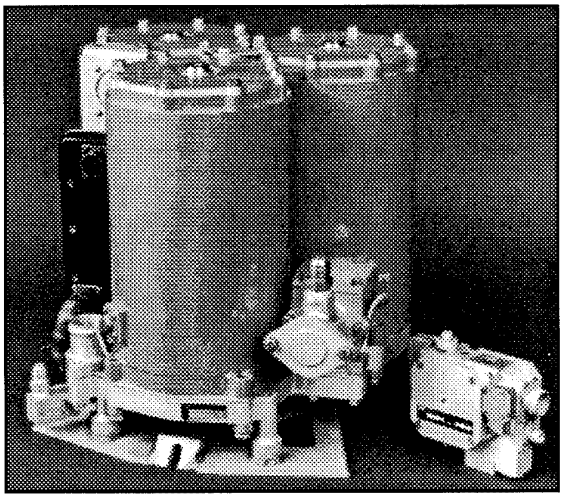

Fig. 8.11 The three bed oxygen concentrator and breathing gas regulator employed in the NGL Advanced Oxygen System Mk 2.

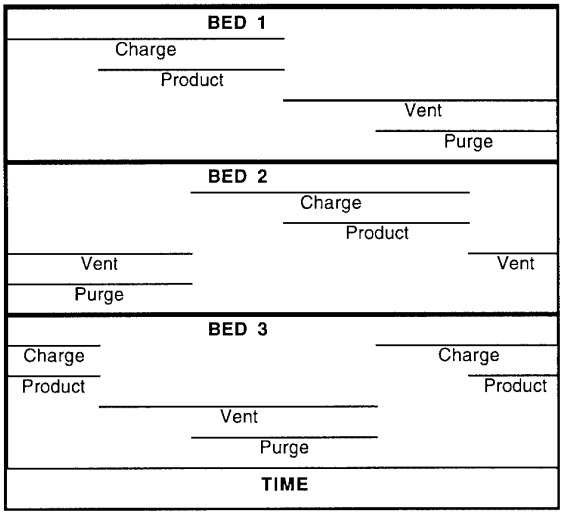

Fig. 8.12 The phasing of the cycles of the NGL three bed oxygen concentrator. The lines indicate when the inlet (charge) and vent valves of each are open; they also indicate when each bed is producing breathing gas and when the bed is being purged.

Product gas pipework

Metal pipework carried product gas from the oxygen concentrator into the pressure cabin and through a non-return valve to the pressure demand regulator (Figure 8.10). A small bleed of product gas was taken from immediately downstream of the non-return valve to the fluidic oxygen sensors. The backup oxygen supply was connected into the product gas pipe upstream of the breathing gas regulator.

Oxygen Sensors

The PO_2 of the product gas at the absolute pressure prevailing in the pressure cabin of the aircraft was monitored by a pair of fluidic PO_2 sensors mounted as a unit within the cockpit. One of the fluidic PO_2 sensors which operated at a PO_2 of 240 ± 10 mm Hg (32 ± 1.3 kPa) provided the closed loop control of the composition of the product gas by switching the cycle speed of the oxygen concentrator. The other fluidic PO_2 sensor switched on a low PO_2 warning light when the PO_2 of the product gas fell below 180 ± 10 mm Hg (24 ± 1.3 kPa).

Flow Sensor

A standard NGL flow sensor at the inlet to the pressure demand regulator operated a doll's eye indicator on the cockpit instrument panel when the gas flow exceeded 2-4 L (NTPD) min^{-1}.

Breathing Gas Regulator and Mask

The flow of product gas from the oxygen concentrator and of oxygen from the backup supply when the latter was selected, was controlled by an NGL low inlet pressure demand regulator (Figure 8.11) mounted on the side wall of the cockpit. The regulator contained a balanced demand valve, and provided safety pressure between ground level and 38,000 feet and pressure breathing between 38,000 feet and 50,000 feet. A compensated dump valve prevented excessive rise of pressure at the outlet of the regulator. The outlet of the regulator was connected through a pull-off connector and hose to a socket to which the inlet hose of a standard RAF type P/Q oxygen mask was secured. The standard seat mounted continuous flow emergency oxygen set was also connected into the mask hose.

Back up Oxygen Supply

The backup supply of oxygen was obtained from the 1,800 lbf in^{-2} gauge (12,400 kPag) gaseous oxygen cylinders normally fitted to the Hunter T Mk 7 which were retained with the AOS Mk 2 installation. The pressure of the backup oxygen supply was reduced to 70 lbf in^{-2} gauge (48 kPag) and delivered into the product gas pipe upstream of the inlet to the breathing gas regulator. The backup supply was selected automatically in the event of the cabin altitude exceeding 25,000 feet. It could also be selected manually by the pilot.

Laboratory Assessment

The complete system was installed in a hypobaric chamber at RAF IAM and its performance determined using a breathing machine and human subjects at rest and during exercise at air supply pressures between 5 and 30 lbf in^{-2} g [35 and 207 kPag] and simulated cabin altitudes up to 30,000 feet. The resistance to breathing imposed by the system met the requirements of the ASCC Air Standard (2) at air supply pressures between 10 and 30 lbf in^{-2} gauge (69-207 kPag). The maximum flow which could be drawn into the mask when the air supply pressure was as low as 8 lbf in^{-2} g [55 kPag] was 100 L (ATPD) min^{-1}.

The mean concentration of oxygen in the product gas delivered to the mask under all conditions of demand and altitude at air supply pressures of 15 to 30 lbf in^{-2} gauge (103-207 kPag) was well above the minimum required to maintain an alveolar PO_2 of 103 mm Hg (13.7 kPa), and at cabin altitudes up to 10,000 feet did not exceed 60%. At cabin altitudes of 15,000 - 20,000 feet the oxygen concentration during quiet and moderate levels of demand was between 65% and 75%. The backup supply of 100% oxygen was delivered rapidly to the mask on the cabin altitude exceeding

25,000 feet and the warning PO_2 sensor operated when the PO_2 of the product gas fell below 170 mm Hg (22.6 kPa).

Flight Trial

A total of 12 sorties were flown with the AOS Mk 2 supplying the pilot in the left hand seat of the IAM Hunter T Mk 7 aircraft. The inlet pressure to the oxygen concentrator, the inlet and outlet pressures of the breathing gas regulator, the PO_2 of the product gas, the inspiratory flow demanded by the pilot, the cabin altitude and +Gz acceleration were recorded throughout flight. The sorties included aerobatics and simulated air combat manoeuvres at aircraft altitudes up to 30,000 feet and sustained +Gz accelerations from +1 to +6 Gz.

The AOS Mk 2 performed satisfactorily throughout all 12 sorties. The inspiratory minute volume demanded by the subject pilot varied between 5 and 35 L (ATPD) min^{-1} with peak inspiratory flows between 20 and 170 L (ATPD) min^{-1}. The swings of the pressure at the outlet of the breathing gas regulator were within the limits of ASCC Air Standard (2) whilst the supply pressure to the oxygen concentrator was greater than 10 lbf in^{-2} gauge (69 kPag). The PO_2 of the product gas corresponded closely with the values obtained during the laboratory assessment, and the concentration of oxygen in the product gas at cabin altitudes below 10,000 feet did not exceed 60%.

F-16A FALCON MOLECULAR SIEVE OXYGEN GENERATING SYSTEM

In the early 1980s, the U.S. Air Force conducted a flight test demonstration of an advanced onboard oxygen generation system on an F-16A high performance fighter. The onboard system was designed and fabricated by Litton, and was a replacement for the liquid oxygen system on the aircraft. The unique features of the MSOGS were the use of a two-bed concentrator and the incorporation of an composition controller to regulate the product oxygen concentration via feedback from an oxygen partial pressure sensor (19).

System Description

The onboard oxygen system, shown schematically in Figure 8.13, consisted of concentrator, oxygen monitor, composition controller, regulator, selector valve, and backup oxygen system (7). The system employed bleed air from the aircraft environmental control system as the source of both oxygen and pressure. Engine bleed air was drawn from the environmental control system downstream of the regenerative heat exchanger, and fed to the concentrator in the temperature range from 25 to 60 °C and pressure range from 25 to 150 lbf in^{-2} gauge (172 to 1,030 kPag).

Oxygen Concentrator

The F-16 concentrator (Figure 8.14) was similar in design to the AV-8 concentrator, but incorporated several design modifications to improve servicing and maintainability. It included a particulate filter, pressure regulator and a continuously rotating inlet control valve which admitted process air, alternately, to each of the two molecular sieve beds. The oxygen concentrator was fitted to the same standard wedge mounting tray as the liquid oxygen converter, and had dimensions of 33.0 wide x 28.4 cm deep x 25.2 cm high. It weighed a total of 13.2 kg and each bed contained 2.5 kg of molecular sieve 5A MG (medical grade).

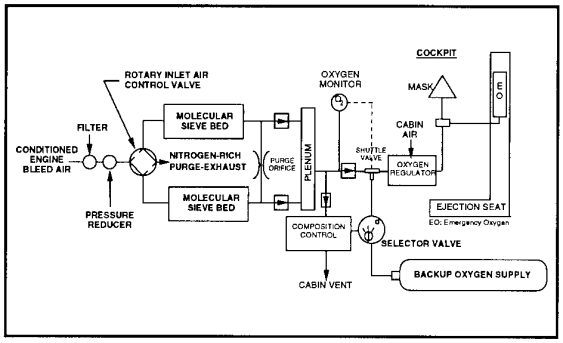

Fig. 8.13 Flow schematic for the molecular sieve oxygen generating system for the F-16A aircraft.

The particulate (coalescence) filter element (0.5 µm pore size) served to remove water from the inlet air stream. A small (0.25 mm) bleed port was incorporated in the bottom of the filter housing to continuously drain condensed water from the filter element. The internal pressure regulator controlled the inlet bleed air pressure to the beds at 37.5 ± 5 lbf in^{-2} gauge (259 ± 35 kPag). The inlet air valve rotated continuously at a constant rate of 6 rpm so that a complete adsorption-desorption cycle occurred every 10 seconds. A pressure relief valve was also included in the rotary valve housing to protect the beds, pipework, and breathing regulator from excessive pressure in the event of failure of the inlet pressure regulator. Gas from the producing molecular sieve bed passed through a check valve into a one liter plenum and through a second 0.5 µm filter into the breathing gas distribution system. A major fraction of the product gas was diverted through a purge orifice and into the downstream end of the desorbing molecular sieve bed to purge nitrogen and other contaminants, which then exited the concentrator via the control valve and exhaust port. The exhaust gases passed through the aircraft skin to ambient. A

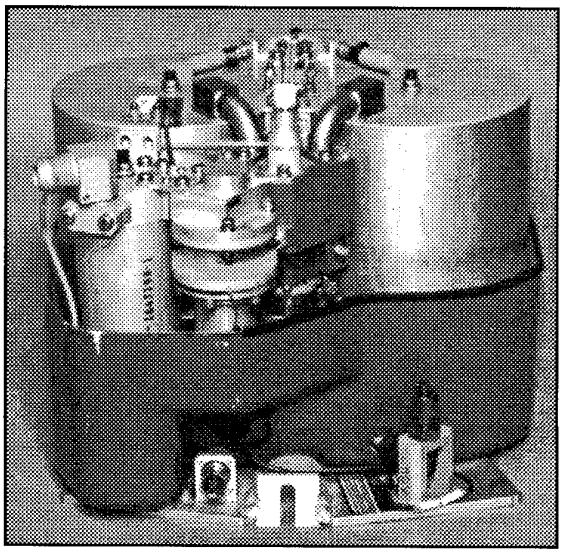

Fig. 8.14 Molecular sieve oxygen concentrator for the F-16A MSOGS(with insulating cover removed).

fiberglass shroud enclosed the concentrator to reduce heat exchange with the environment.

Cockpit Mounted Components

The cockpit-mounted components of the F-16 MSOGS included the regulator/oxygen monitor/composition controller which were contained in a single assembly, the selector valve, and the backup oxygen supply (Fig. 8.15).

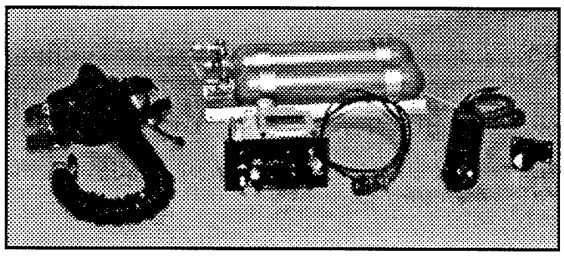

Fig. 8.15 Cockpit Components of the F-16A Molecular Sieve Oxygen Generation System.

Regulator

The regulator was a special to task, low inlet pressure demand type, designed to deliver peak inspiratory flows up to 200 L (ATPD) min^{-1} at reduced suction pressure to facilitate the performance of a high-G straining procedure. A press-to-test button on the regulator provided 10 inch wg (2.5 kPag) pressure to the mask to test mask fit. The inlet pressure to the regulator was approximately 37.5 lbf in^{-2} gauge (260 kPag), depending on the demand flow rate and pressure drop across the concentrator. When supplied by the backup oxygen supply, the inlet pressure to the regulator was approximately 60 lbf in^{-2} g (414 kPag). The regulator provided a positive safety pressure of 1 inch wg (0.25 kPag) at all cabin altitudes up to 38,000 feet. Above this cabin altitude, the regulator delivered oxygen from the backup supply at a positive pressure which increased linearly with fall of cabin pressure up to a maximum value of 22 inch wg (5.5 kPag).

Composition Controller

A composition controller was incorporated in the F-16 MSOGS to limit the concentration of oxygen in the breathing gas, and thus reduce the possibility of acceleration induced lung collapse as a result of high-G maneuvers. Operation of the controller was based on the predictable reduction in oxygen concentration with increased mass flow through the concentrator. Thus, composition control was achieved by increasing the air flow through the concentrator and venting the excess product gas to the cabin.

Oxygen Monitor

The MSOGS employed a polarographic-type oxygen monitor to measure the partial pressure of oxygen in the breathing gas produced by the concentrator. The electrical signal from the oxygen monitor was sent to the composition controller, where it served to regulate a pilot valve that allowed an aneroid to bleed the concentrator depending on product oxygen concentration. In the event that oxygen partial pressure fell below 195 mm Hg (26 kPa), the monitor turned on the OXY- LOW warning light and automatically activated the backup oxygen supply.

Selector Valve

The MSOGS selector valve was used to manually or automatically select the breathing gas source from either the MSOGS concentrator or the backup oxygen supply (BOS). The selector had three positions: BOS OFF, NORMAL, and BOS ON. The selector was placed in the BOS OFF position when the system was not operating. This was to mechanically lock the backup oxygen supply and thus prevent automatic depletion at engine turn-off. The NORMAL mode was selected for routine flying conditions. The system (when using the BOS by manual or automatic selection) would automatically revert to MSOGS supply when the BOS was depleted, and the OXY- LOW indicator would remain illuminated. The pilot could select the BOS ON mode of operation at any time. In the BOS ON mode, the BOS oxygen would override all automatic control functions except that the system would automatically revert to OBOG supply when the BOS was depleted.

Backup Oxygen Supply

The backup oxygen system consisted of two 0.8 liter (50 in^3) gaseous oxygen cylinders pressurized to 2000 lbf in^{-2} (13,800 kPag) giving a combined capacity of 200 liters (NTP). The two bottles were connected in parallel with the necessary fittings for ground filling. An aneroid switch incorporated in the regulator/monitor would automatically switch to BOS whenever the cabin altitude exceeded 25,000 feet provided that the NORMAL mode was selected. In the NORMAL mode, switchover to BOS occurred when either (a) oxygen concentration was less than 195 mm Hg, (b) cabin altitude was greater than 25,000 feet pressure altitude, or (c) the concentrator product pressure was below a preset value, nominally 10 lbf in^{-2} gauge (69 kPag).

Pilot Equipment

Other ancillary equipment included with the MSOGS was the oronasal mask, a standard USAF CRU-60/P connector and standard oxygen hoses. A modified RAF type P/Q oronasal mask and the USAF MBU-5/P or 12/P masks were used in the flight test program. Resistance to breathing was less in the P/Q mask because it has separate inspiratory and expiratory valves versus the combined valve in the USAF masks. For the flight demonstration, the P/Q mask was modified to be compatible with standard USAF communications systems and to allow the mask to be attached to the standard USAF HGU-26/P bayonet receivers.

Performance Evaluation (Man-Rating)

The F-16A Molecular Sieve Oxygen Generating System was extensively tested at the Armstrong Laboratory to verify component and system performance prior to the flight test program (15). The MSOGS product gas flow, pressure and composition were measured as functions of bleed air pressure and temperature, cabin altitude, exhaust pressure (aircraft altitude) and pilot workload (respiratory minute volume). Rapid decompression and acceleration tests were also accomplished.

The MSOGS performance is summarized in Figure 8.16, which shows breathing gas composition as a function of

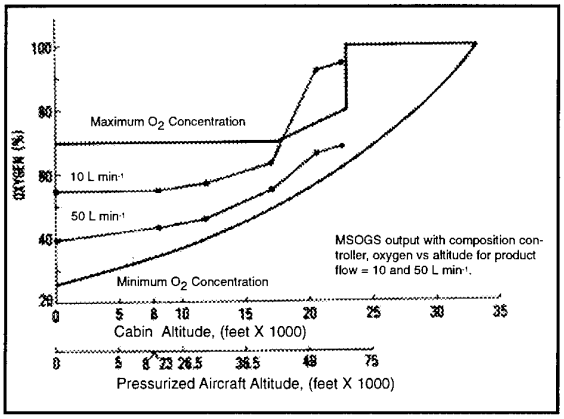

Fig. 8.16 Performance of the F-16A molecular sieve oxygen generation system. Data from Horch et al (15).

cabin altitude. The minimum and maximum oxygen concentration lines depict the performance specifications; the lower bound to maintain partial pressure of oxygen at greater than 195 mm Hg, and the upper bound to limit the breathing gas composition to 70% oxygen up to a cabin altitude of 17,000 feet. The two parametric curves show system performance at minute volumes of 10 and 50 L min^{-1} (ATPD) and indicate that the composition controller was effective at the demand flows likely to be encountered in high performance aerial combat maneuvers.

Man-rating of the MSOGS was conducted with five human subjects performing simulated inflight activities, including anti-G straining maneuvers (M-1), radio transmission, light and medium workload (bicycle ergometer) through the full range of normal cabin altitudes (15). Decompression testing was conducted to final altitudes of 23,000 and 40,000 feet with four subjects, as was acceleration testing to a maximum of +9 Gz on the Brooks AFB human centrifuge.

Flight Test Evaluation

Flight test of the MSOGS was conducted in the F-16A at Hill AFB UT from August 1982 through October 1983 (10). Over 116 hours of test flight were logged in 100 flights by at least 17 different USAF pilots, covering the full operational envelope of the F-16 aircraft. The purpose of the flight test was to evaluate the MSOGS for the F-16 tactical fighter mission. Specific test objectives were to determine pilot acceptance of the integrated gas delivery system (flows, pressure, oxygen concentration) throughout the aircraft flight envelope, validate system-airframe interface and MSOGS installation integrity, and make a qualitative assessment of system operational compatibility, suitability, reliability, maintainability, and safety.

Within the scope of these objectives, the MSOGS demonstrated excellent potential for improved oxygen system maintainability, increased safety, and improved pilot comfort for all of the F-16 tactical fighter missions. Pilot response to the MSOGS breathing system was overwhelmingly positive.

The formal flight test program was completed in October 1983. In anticipation of an engineering change proposal to retrofit the F-16 fleet, Litton agreed to continue maintenance support of the MSOGS in the test aircraft. Following minor improvements to the MSOG system - e.g, addition of a water drain port to the filter assembly, addition of a safety pressure on/off toggle switch and installation of a felt collar in throat of regulator demand valve to reduce noise, modification of selector valve from 4-position to 3-position, and redesign of the controller to employ electrical in place of pneumatic drive - a second series of flight tests was begun in November 1983. In the second series of flights, the onboard oxygen system accumulated an additional 220 hours of flight time in 148 sorties. Aircrew acceptance of the system was excellent, and no major problems were reported.

Owing to financial considerations, the Air Force elected not to retrofit MSOGS into the F-16 fleet during the C/D-model upgrade in 1983. As a result, the F-16A MSOGS test aircraft was reverted to standard LOX configuration in May 1984. Introduction of MSOGS into the F-16 fleet remains an attractive option for future upgrades or derivatives of the F-16 aircraft.

USAF ADVANCED OXYGEN SYSTEM (AOS)

The Advanced Oxygen System produced for the Armstrong Laboratory (USAF) by Normalair Garrett, Ltd, was a laboratory model of a complete aircraft breathing system. Although not intended for installation in any current aircraft, the AOS was nonetheless designed to operate in a simulated airborne environment, supplied by aircraft resources, and to be compatible with aircraft weight and bulk limitations. The purpose of the AOS was to serve as a laboratory tool for simulation of advanced aircraft breathing systems (25). As a demonstrator of advanced flight equipment, the AOS was potentially refineable to a flight capable system.

AOS Description

The AOS consisted of a two-man molecular sieve oxygen generation system with feedback control of the oxygen concentration in the breathing gas; two seat mounted regulator packages with integral personal equipment connector (PEC) and anti-G valve; personal protective equipment including high pressure breathing masks and helmets, and chest counterpressure garments; fully functional controls and indicators; seat mounted emergency oxygen assemblies including selector valves and large emergency stores (Figure 8.17). The AOS was designed to perform to the physiological breathing requirements of Chapter 5, while providing altitude protection to at least 60,000 feet and assisted pressure breathing during G-loading. Although it did not include chemical warfare defense equipment (e.g. respirator, protective garments), the AOS did supply blown filtered air for respirator ventilation and connections through the PEC for a liquid cooled vest, commonly proposed for personal thermal control under protective garments. It also incorporated a separate mask hose sensing line to allow compensation for a flow resistive chemical defense filter pack placed in the final breathing line. Impermeable lip seals, self-sealing check valves, and a unique flushing gas flow provided protection against contamination during PEC coupling and uncoupling actions.

AOS Oxygen Concentrator

The AOS OBOGS was a two-bed design using zeolite 5A in cylindrical beds, mounted on a conventional liquid oxygen

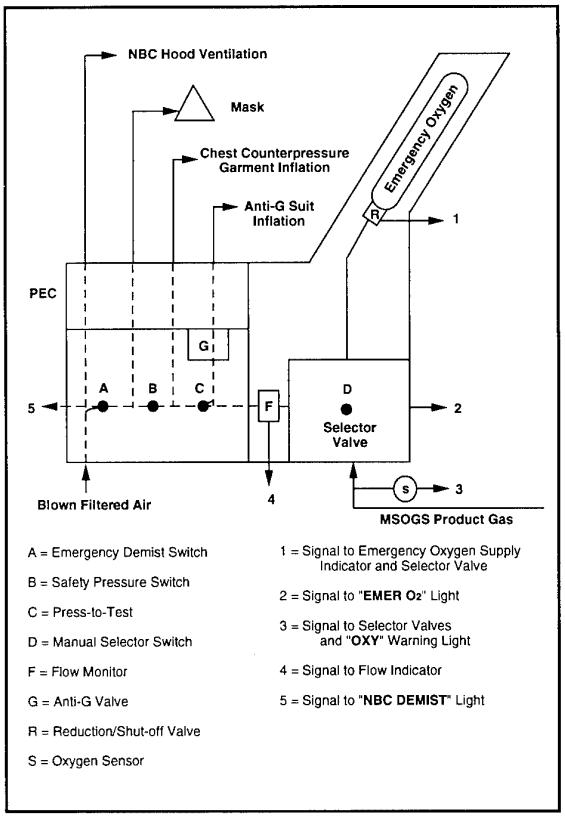

Fig. 8.17 Flow schematic for the USAF advanced oxygen system (AOS).

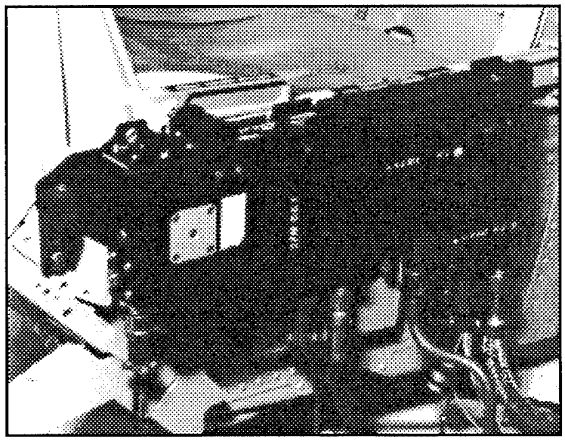

Fig. 8.18 Seat-mounted regulator package and personal equipment connector (PEC) for the USAF advanced oxygen system.

converter wedge plate. The AOS concentrator was designed to accommodate two crewmen with a total peak flow of 400 L (ATP) min^{-1}, and had overall envelope dimensions of 42 x 36 x 36 cm. It contained several innovations. The AOS unit was pneumatically powered, utilizing an air driven and timed, piston actuated, shuttle type control valve to cycle regulated bleed air into the molecular sieve beds. Thus oxygen generation was totally independent of electrical power, which meant that the molecular sieve beds could not be damaged by power failure or the application of bleed air pressure without electrical power. Secondly, the AOS concentrator beds delivered product gas into a mixing plenum which eliminated cyclic oxygen concentration variations due to slight differences between the beds, and maintained nearly constant product gas pressure under heavy cyclic demand. Thirdly, control of oxygen concentration was achieved using total product flow as the control mechanism and the signal from a zeolite oxygen partial pressure sensor as the control variable.

Breathing Regulator

The AOS breathing regulator package was designed for mounting on the side of an ejection seat pan with its upper surface near arm rest level (Figure 8.18). It was rectangular in outline, 41 long x 16 cm deep and 4 cm thick. The fact that no current US high performance aircraft seat/cockpit configuration can accommodate ejection seat mounting is one important reason the AOS was not intended for any present aircraft. Nevertheless, this mounting arrangement remains preferable for new aircraft and/or seat designs. It provides fingertip control position for the aircrew, potentially even under G-loading. Properly configured, it can allow easy access for any required maintenance, and, of course, the regulator will accompany the crewman during ejection. The upper surface of the regulator package included, from front to rear, an emergency oxygen selector switch (on, auto, off), the breathing mode toggle --press-to-test, normal (which included safety pressure), and demand (no safety pressure). It also included a respirator demist on-off control switch, and the anti-G valve mode toggle (press-to-test, ready pressure, normal). Aircraft services were applied from below.

The AOS regulator accommodated demand flows of 60 L min^{-1} minute volume, 200 L (ATPD) min^{-1} peak flow, at an inlet pressure of 10 lbf in^{-2} gauge (69 kPag), through a balanced demand valve design. With safety pressure selected (normal mode), mask pressure remained positive at flows up to at least 100 L (ATPD) min^{-1}. Mask pressure swings met the ASCC Standard (2). Automatic safety pressure (1.0 to 2.0 inch wg (0.25-0.5 kPa)), including torso and lower body garment ready pressure, activated at aircraft altitudes above 39,000 feet. Positive pressure breathing was provided at cabin altitudes above 39,000 feet, increasing linearly with fall of cabin pressure to a maximum of 80 mm Hg (10.7 kPag) at about 56,000 feet. During positive pressure breathing, the anti-G trousers provided lower body counterpressure at four times the breathing pressure. When cabin altitude exceeded 25,000 feet, emergency oxygen was automatically selected. Thus at an altitude of 60,000 feet, the delivered oxygen pressure was 135 mm Hg absolute (18 kPaa). This system met ASCC physiological standards for "get-me-down" protection up to 80,000 feet (1). Assisted positive pressure breathing was also provided during exposure to $+G_z$ forces, at 12 mm Hg (1.6 kPag) per G above +4 Gz, to a maximum of 60 mm Hg (8 kPag) at +9 Gz.

The regulator assembly also incorporated a chemical defense respirator demist function, which used about 15 L min^{-1} of OBOGS gas flow to entrain an additional 45 L min^{-1} of filtered cabin air through an injector. A volumetric flow of 50-60 L (ATPD) min^{-1} was provided at an outlet pressure of about 3 inch wg (0.75 kPag), at altitudes up to 50,000 feet. In the event of ejection at altitude, emergency oxygen was employed to drive the injector mechanism.

The anti-G valve, which was integral to the regulator assembly, was a miniaturized high flow design. Filtered, regulated bleed air acted as the driving gas for anti-G suit inflation, but pneumatic control of the valve was accomplished with clean OBOGS product gas or emergency oxygen. Loss of bleed air pressure allowed oxygen inflation of the G-suit (e.g., during high altitude escape). The anti-G valve was pneumatically controlled and provided a ready pressure of 0.2 lbf $in^{-2}g$ (1.4 kPag), as well as the standard anti-G suit inflation schedule. The anti-G valve contained a press-to-test function.

The personal equipment connector attached directly to the upper surface of the regulator assembly with a simple, one-step locking procedure. Release, which could be accomplished easily and quickly with either hand, was a two-step manual process (squeeze and pull) to prevent inadvertent disconnection. The PEC released from the regulator automatically upon man-seat separation during the ejection sequence. The connector passed all aircraft supplied services to the crewmember: breathing gas (includes counterpressure vest inflation), filtered respirator ventilation gas, anti-G suit inflation gas, cooling liquid for personal thermal control, breathing pressure sensing line, and communications circuits.

Pressure Equipment

The pressure equipment chosen for use with the AOS was the French VHA 90 high altitude protective ensemble, used in conjunction with standard USAF CSU-13B/P anti-G trousers. The VHA 90, integrated by Intertechnique, Plaisir, France, consisted of a low profile, low resistance, high pressure breathing mask with a combined inhalation/exhalation valve; a helmet containing aural and occipital bladders for automatic mask tensioning, and external ear pressurization above about 40 mm Hg (5.3 kPag) breathing pressure; and an upper body counterpressure vest with integral flotation collar. The system had been laboratory tested to altitudes above 60,000 feet. A standard USAF HGU-55/P helmet was modified with the tensioning bladders, ear protection, and mask retention system compatible with the French equipment.

Emergency Oxygen

The AOS provided each crewmember with a seat mounted high pressure cylinder of 2.2 liter internal volume, containing about 370 liter (STP) of oxygen at 2500 lbf in^{-2} gauge (17,200 kPag). Dimensions of the assembly, including on-off (standby) valve, pressure reducer, pressure gauge, and charging valve, were 48 cm long by 10 cm in diameter. With the cylinder in the standby-on mode, emergency oxygen could be selected manually by a control switch on the regulator assembly, or automatically when cabin altitude exceeded 25,000 feet or when OBOGS product gas pressure oxygen partial pressure fell below a minimum acceptable value. After emergency oxygen was depleted, OBOGS gas was again supplied to the breathing system regardless of pressures available.

USAF TACTICAL LIFE SUPPORT SYSTEM

The USAF Tactical Life Support System (TLSS) was a flight demonstration integrated life support system developed for the USAF by Boeing (8). The TLSS breathing system incorporated many features of the Advanced Oxygen System (AOS) described above, but added chemical defense protection, flashblindness and laser eye protection, and integrated flight garmentry to form a complete personal protective system. This effort was the first USAF attempt to design a flyable system with integrated anti-G, high altitude, chemical defense, thermal, and eye protection, while simultaneously improving breathing characteristics, reliability and maintainability, and logistic supportability. The hardware was designed for flight test on an F-15D aircraft.

TLSS Breathing System Description

Built to essentially the same specification as the USAF Advanced Oxygen System, the TLSS breathing system offered nearly identical performance, giving altitude protection to 60,000 feet, and assisted pressure breathing during acceleration (+4 to +9 Gz). The breathing system consisted of an oxygen generator; airframe mounted standby oxygen supply; cockpit oxygen control panel; ejection seat mounted selector valve, breathing regulator, personal equipment connector, and emergency oxygen. Pilot equipment included counterpressure garments and high pressure breathing mask/helmet/CD respirator; and appropriate interconnecting distribution tubing and connectors. Because of different suppliers, and the fact that it would have to operate within the constraints of an existing airframe, crew station, and ejection seat, TLSS hardware differed significantly from the corresponding AOS elements (11). Although the TLSS breathing system was designed with a two-man capacity, only one crewman wore the system during flight test. The other crewmember, operating as safety pilot, used conventional protective gear and a standard oxygen supply.

Oxygen Generator

The environmental control system equipment bay of the F-15D housed the Tactical Life Support System oxygen concentrator, which was fed by conditioned bleed air from the anti-fog heat exchanger through a centrifugal filter. The oxygen concentrator (NGL) was a three-bed tandem configuration using MG-3 zeolite, similar to half of a B-lB MSOGS concentrator. As in the B-lB MSOGS, electronically controlled solenoid valves and channels in the base of the assembly controlled the feed air charge, product gas flow, sieve bed purge, and vent cycle of the concentrator. In contrast to the B-lB, however, the TLSS oxygen concentration was controlled by varying the cycle time of the molecular sieve beds, with feedback provided by a fluidic oxygen partial pressure sensor.

Emergency Breathing Supplies

TLSS included a large, airframe-mounted standby supply of 100% gaseous oxygen at 2000 lbf in^{-2} g (13,800 kPag) nominal pressure in the F-15D liquid oxygen converter bay. This oxygen source provided approximately 20 minutes of back-up breathing capability for two crewmen. It could be selected manually from a switch on the cockpit oxygen control panel, or activated automatically if cabin altitude exceeded 25,000 feet or if the molecular sieve oxygen generator failed. Also, the seat mounted emergency oxygen supply ("bailout bottle") was retained and slightly enlarged to provide the additional duration needed in case of extreme high altitude escape. At low altitude (below 9,000 feet), the cabin

air bypass valve, a unique TLSS feature, allowed the crew to breathe cabin air in order to conserve standby oxygen during cockpit alert or low altitude emergency.

Cockpit Controls

The cockpit oxygen control panel contained a gauge presenting standby oxygen contents, a breathing gas flow blinker, and indicator lights for standby oxygen or cabin air selection. Panel switches included the main system breathing gas source selector, and a safety pressure on/off, press-to-test toggle. Separate panels controlled the CD visor demist electrical blower, the vapor-cycle personal thermal control unit, and the electronic servo anti-G valve.

Seat Mounted Equipment

Mounted in the pan of the ACES II ejection seat were the selector valve, low pressure breathing regulator, and seat portion of the personal equipment connector (PEC). The selector valve provided either primary breathing gas flow (oxygen concentrator product) or, when selected, standby oxygen. The breathing regulator operated with inlet pressure as low as 10 lbf in^{-2} gauge (69 kPag), to provide demand flow of 60 L (ATPD) min^{-1} with 200 L(ATPD) min^{-1} peaks. Selectable safety pressure maintained positive mask cavity pressure with flow up to 100 L (ATPD) min^{-1}. Mask cavity pressure swings met the ASCC Standard (2). Positive pressure breathing was applied at cabin altitudes in excess of 39,000 feet, or during high $+G_z$ maneuvers, to maximums of 70 and 60 mm Hg (9.3 and 8 kPag), respectively. A pneumatic signal from the panel mounted anti-G valve drove the pressure breathing under +Gz function of the regulator. The digital electronic anti-G valve had an inherent altitude bias and received a redundant electronic pressure signal from the breathing line to inflate the G-suit at 4x breathing pressure for high altitude "get-me-down" protection. The PEC was placed in the right rear corner of the seat, with an extension upon the arm rest serving as receptacle for the pilot mounted portion of the connector. Services passing through the PEC included breathing gas, anti-G suit inflation gas, CD visor demist gas, and communications. A separate connector provided liquid coolant for personal thermal control.

Personal Equipment

The TLSS pilot mounted equipment consisted of an integrated flight coverall, new high pressure breathing mask, and lightweight Kevlar helmet with two variations of CD respirator - one designed to counter vapor threat only, and the other capable of protecting against liquid and vapor agent challenge. The flight coverall was made of charcoal impregnated Nomex fabric. The upper torso garment (four sizes) contained an integral chest counterpressure bladder, while the lower body garment (six sizes) contained integral anti-G suit bladders with extended coverage. The two modules laced together to form a single, easily donned and doffed integrated flight suit. Additional lacings provided further sizing adjustment. The chest counterpressure bladder balanced mask pressure by receiving gas at breathing pressure directly from the mask hose. The lower body pressure bladders were inflated by the anti-G valve either in accordance with the anti-G inflation schedule or at 4-times breathing pressure during pressure breathing at high altitude. The breathing mask, in conjunction with an occipital bladder in the helmet for automatic tensioning, could retain at least 70 mm Hg (9.3 kPag) positive breathing pressure, even under severe G-loading conditions. Low pressure drop characteristics of the mask inlet and exhalation valves contributed to the improved breathing resistance of the entire system. The same basic mask configuration was integral to both chemical defense respirators, carrying the high pressure capability and improved characteristics through the entire family of breathing hardware.

The Tactical Life Support System was man-rated at the USAF Armstrong Laboratory in early 1988. Portions of the TLSS system, namely the man-side personal equipment (but not the molecular sieve oxygen concentrator) were flight tested in an F-15D test aircraft at Edwards AFB CA in 1989 (13). The TLSS feature of positive pressure breathing for G-protection received strong endorsement from the flight test community. This endorsement resulted in a follow on program to develop the Combined Advanced Technology Enhanced Design G-Ensemble (COMBAT EDGE) program, to perfect positive pressure breathing for enhanced G-protection in high performance aircraft (20). COMBAT EDGE is now operational in the USAF inventory of F-16 aircraft.

B-1B MOLECULAR SIEVE OXYGEN GENERATING SYSTEM

The breathing gas system onboard the B-1B strategic bomber is the first operational molecular sieve system for the US Air Force. Built by Normalair-Garrett Ltd under contract to Rockwell International, the B-1B MSOG system consists of an oxygen concentrator assembly, a backup oxygen supply and release valve, two downstream system purge valves, and six breathing regulators. The breathing gas pipework installed on the B-1A prototype aircraft (which contained a fluomine-based onboard oxygen generator - see Chapter 3) was enlarged in diameter for the B-1B aircraft to accommodate the lower system operating pressure of the MSOGS. During most B-1B aircraft operations, cabin air, pressurized to a nominal altitude of 8,000 feet, serves as the primary aircrew breathing gas. The operators consider the MSOGS to be a secondary breathing gas supply. An airframe mounted backup supply of high pressure (1,800 lbf in^{-2} g)(12,400 kPag) gaseous oxygen (separate from the MSOGS) provides a tertiary breathing gas source. Finally, a seat or parachute pack emergency bottle is the last of the redundant breathing gas sources. Figure 8.19 is a schematic diagram of the B-1B aircrew breathing system.

Concentrator Assembly

The MSOGS concentrator contains six beds of MG-3 (13X type) zeolite arranged in two parallel rows of three canisters (Figure 8.20). The assembly is about 60 cm long, 40 cm high, by 50 cm deep, weighs about 44 kg, and is installed at the rear of the central equipment bay of the aircraft, accessible to the crew in flight. The concentrator assembly itself processes engine bleed air at temperatures up to 138 °C and pressures up to 75 lbf in^{-2} g (517 kPag). The input air is first cooled to about 38 °C in a two-pass, gas-liquid heat exchanger (precooler). A water extractor and 0.6 μm filter remove condensed water and particulates. After pressure reduction to a nominal maximum value of 35 lbf in^{-2} g (241

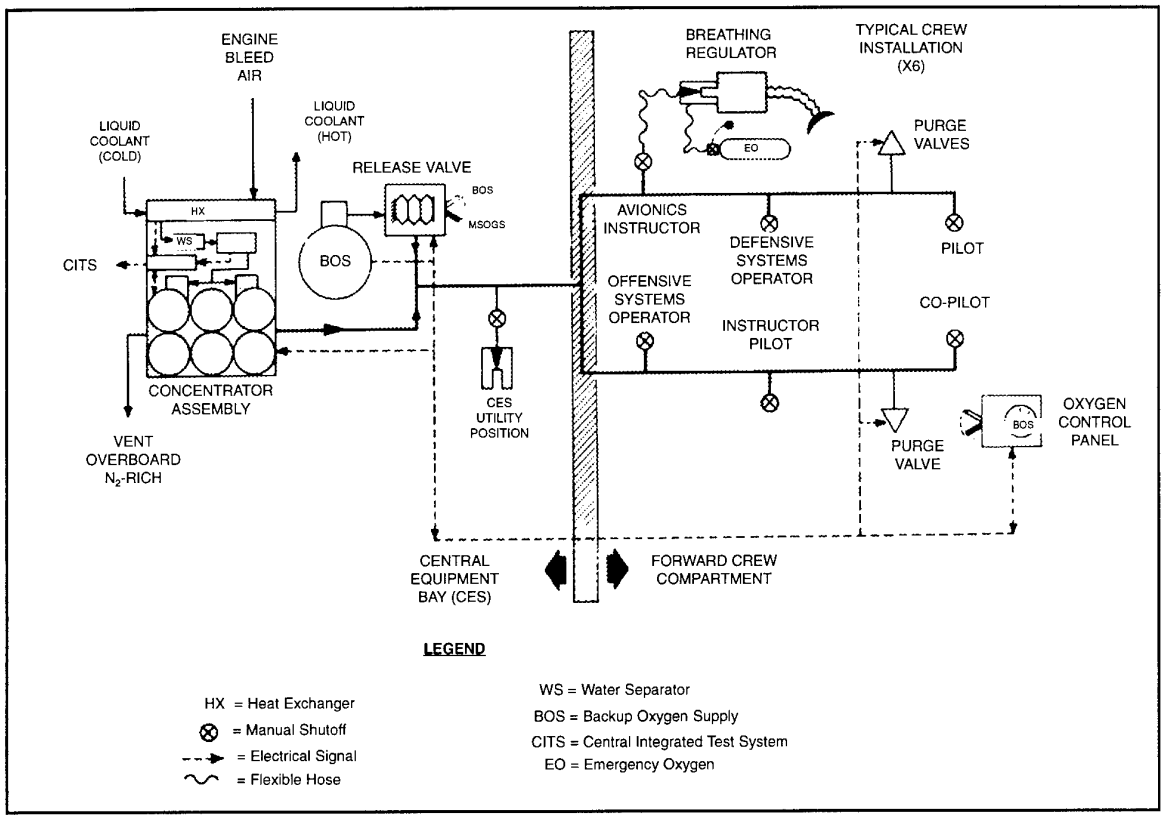

Fig. 8.19 Flow schematic diagram of the B-1B molecular sieve oxygen generating system.

kPag), conditioned bleed air enters the concentrator beds through electrical solenoid valves. Similar to other NGL concentrator designs, the molecular sieve bed inlet valves, vent valves, purge channels, and product gas plenum are integral to the base of the concentrator assembly.

An electronic control unit operates the solenoid inlet and vent valves, in sequence, to produce the correct pattern of air charge, product gas flow, purge flow, and vent to ambient in each of the six zeolite beds. The control unit drives each valve on a fixed 9 second cycle, chosen to optimize product gas oxygen concentration over the normal range of operating pressure, temperature, and demand flow. Oxygen concentration of the product gas is optimized but not controlled. The electronic module also processes signals indicating precooler outlet air temperature, pressure drop across the particulate filter, and individual bed pressure. These signals provide sound criteria for assessment of the performance of the concentrator, and thereby enable the control unit to signal the aircraft central integrated test system in case of concentrator faults or failure.

The MSOGS concentrator is designed to supply 160 L (ATPD) min^{-1} breathing gas flow for a crew of six (four primary aircrew plus two instructor pilots). This allows a minute volume of 26.7 L (ATPD) for each crew member, meeting the requirements of MIL-D-19326H (28). Each of the normal combat crew of four is provided minute volumes up to 40 L (ATPD), sufficient to sustain moderate to heavy workloads as might be encountered during operational mission activities (12)(See Chapter 5). When the crew cabin is depressurized, the concentrator produces gas with a minimum oxygen concentration equivalent to breathing air at sea level for system demand flows up to 160 L (ATPD) min^{-1}. With the cabin pressurized, the minimum oxygen concentration produced is sufficient to prevent alveolar oxygen tension falling below 30 mm Hg upon rapid decompression, thereby precluding aircrew incapacitation due to transient hypoxia (See Chapter 5). The normal bleed air pressure of greater than 25 lbf in^{-2} g (172 kPag) at the concentrator inlet produces breathing gas at a pressure sufficient to drive the breathing regulator (10 lbf in^{-2} gauge)(69 kPag).

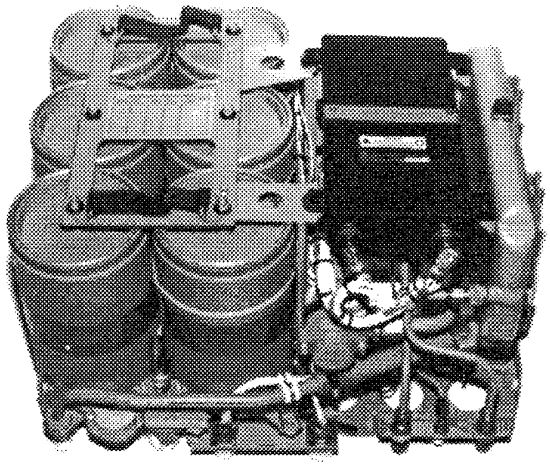

Fig. 8.20 Molecular sieve oxygen concentrator for the B-1B aircraft.

Release Valve

The Back-up Oxygen Supply (BOS) release valve is located adjacent to the concentrator assembly in the central equipment bay, and releases 100 percent oxygen from the backup supply when the cabin altitude exceeds 27,000 (± 2,000) feet, or when activated by the crew. The crew can open the valve by manually turning a switch on the valve case or by an electrical toggle on the oxygen control panel at the copilot station. An internal aneroid opens the valve automatically when cabin altitude exceeds 27,000 feet. Upon aircraft descent to below 27,000 feet, or cabin repressurization, the BOS release valve automatically closes and MSOGS gas flow is resumed. The aneroid can also be depressurized at ground level for test of the automatic release mode. If the backup oxygen supply is depleted, breathing gas is again provided by the MSOGS concentrator regardless of the position of the release valve.

Purge Valves

Two purge valves are located in the oxygen distribution system near the pilot and copilot flight stations. The function of these valves is to dump the gas in the distribution system to cabin ambient when the release valve opens to supply 100 percent backup oxygen. Whenever backup oxygen is selected, either automatically or manually, it must be delivered to the crew as rapidly as possible. The large volume (3.5 liters) of MSOGS product gas held in the 15 meters of delivery pipework between the concentrator and the forward crew stations, if not purged from the system, would delay the delivery of 100 percent oxygen. The purge valves open for a short time (approximately 0.5 sec), to dump gas at a very high flow rate, and then close quickly to avoid depletion of the backup supply. The release valve generates an electrical signal as it opens, initiating this action of the purge valve.

Breathing Regulators

Each of the six aircrew positions has a non-dilution, low inlet pressure breathing regulator. At the four primary crew stations, the regulator is mounted on the ejection seat; at the instructor stations, the regulator is carried on a parachute harness mount. The regulator is small (7 x 7 x 14 cm) and lightweight (0.45 kg) for minimal encumbrance when worn on the harness. The breathing regulator incorporates an anti-suffocation valve which is set to open between -5.0 and -7.0 inch wg (-1.2 to -1.7 kPag). It also features a compensated outlet relief valve to limit mask pressure to less than 22.0 inch wg (5.5 kPag) during decompression, and a selectable safety pressure mode which maintains positive mask pressure at steady flows up to 126 L (ATPD) min^{-1}. This flow is equal to the peak instantaneous inspiratory flow expected with a 40 L minute volume. Above 30,000 feet altitude, the regulator automatically supplies pressure breathing which progressively increases outlet pressure to 8.0 to 11.0 inch wg (2.0 - 2.7 kPag) at 45,000 feet. If safety pressure is selected, outlet pressure is 1.0 to 1.5 inch wg (0.25 - 0.37 kPag) higher than in the demand (normal) mode.

Performance

The MSOGS was man-rated by the USAF in 1985 (6,24), and the system was later installed in all B-1B aircraft produced. During the eight year operational experience , the performance history of the MSOGS has been largely satisfactory. Some problems have been noted with "dusting" of the molecular sieve material; i.e., the appearance of extremely fine zeolite powder in the oxygen lines and regulatosr downstream of the oxygen concentrator. This is believed to be due to inadequate bed retention and/or the exposure of the molecular sieve beds to liquid water. The short term solution to the dusting problem has been the installation of a particulate filter in the concentrator outlet line. The permanent solution, however, appears to be bed immobilization with an inert polymeric material as discussed in Chapter 6.

A secondary problem with the B-1B MSOGS has been an occasional case of delayed otitic barotrauma ("aviator's ear") following extended missions, because of the typically high oxygen concentration delivered to the crew member (see Chapter 5). As discussed in Chapters 5 & 6, the solution to long term breathing of elevated oxygen concentration is the inclusion of composition control in the MSOG system, or, (less desirable), the incorporation of an air dilution regulator, with appropriate compensation for less than 99.5% oxygen, and potential exposure to chemical agents.

YA-7F ATTACK FIGHTER MOLECULAR SIEVE OXYGEN GENERATING SYTEM

In the late 1980's, the USAF modified two A-7D "Corsair" attack fighters for evaluation in the roles of close air support and battlefield interdiction. While the primary modification to the aircraft was the installation of a modern afterburning turbofan engine, improvements were also made to other subsystems including the environmental control, electrical, fuel, and hydraulic systems. A molecular sieve onboard oxygen generating system was also installed (16). After program go-ahead in 1987, the contractor, LTV Aerospace and Defense Company, Dallas Texas, modified two A-7D low altitude night attack airframes to the YA-7F configuration, which was a single engine, single seat, fighter attack aircraft.

Description

The molecular sieve oxygen generating systems (MSOGS) on the YA-7F replaced the LOX system and provided an oxygen-enriched breathing gas to the pilot. Figure 8.21 is a schematic of the oxygen system, which consisted of an oxygen concentrator (Litton), heat exchanger, regulator, mask, and molecular sieve-filled backup oxygen system (BOS).

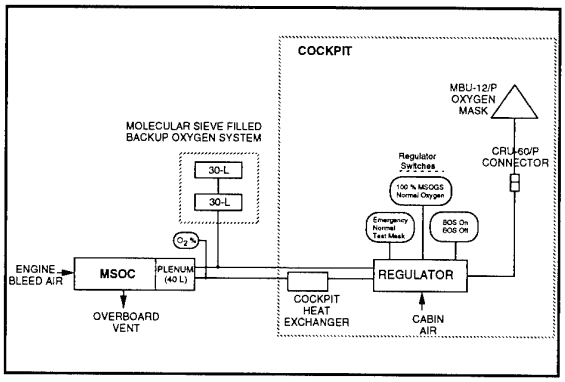

Fig. 8.21 Flow schematic for the YA-7F molecular sieve oxygen generating system.

Engine bleed air, after passing through the precooler was supplied to the MSOGS concentrator. A temperature sensor was used to control a modulating valve which added warm bleed air, if necessary, to the MSOGS inlet.

The MSOGS product gas was fed directly to the dilution regulator, which mixed the gas with cabin air to vary the oxygen concentration as a function of cabin altitude. The oxygen regulator was adapted from the standard CRU-73/A and adjusted for the 93% oxygen supplied by the MSOG concentrator rather than 99.5% oxygen normally supplied by a LOX convertor. Although not part of the MSOGS, an electrochemical oxygen sensor was added to the system during the flight test program, so that oxygen partial pressure of the MOSGS product gas could be monitored.

Backup Oxygen Supply

The backup oxygen system (BOS) consisted of two cylinders and a molecular sieve filled plenum that stored gaseous oxygen taken from the MSOGS product line. The BOS stored 100 liters (NTP) of oxygen at 85 lbf in^{-2} gauge (586 kPag), which included 60 liters in the two cylinders and 40 liters within the concentrator. It was estimated that this could provide approximately 30 minutes of breathing gas to the pilot (breathing at a rate of 20 L min^{-1} at ground level or 30 L min^{-1} at 10,000 feet). A valve on the product gas line allowed product gas to recharge the BOS without interrupting flow to the regulator. The BOS was not to allowed to recharge if the line pressure was below 50 lbf in^{-2} gauge (345 kPag). A complete recharge of the BOS could occur if the line pressure was 85 lbf in^{-2} gauge (586 kPag) or above. The oxygen regulator was modified to provide a capability to switch manually from MSOGS operation to the BOS. Additionally, the pressure gauge on the regulator was modified to display the BOS pressure.

Performance

The MSOGS performance was satisfactory throughout the YA-7F test program (16). The concentrator provided between 93 and 95 percent oxygen to the regulator during flight. Bleed air pressure varied between about 90 and 120 lbf in^{-2} gauge (621 - 827 kPag) at and above cruise power settings, which was adequate to replenish and maintain BOS storage pressure at 85 lbf in^{-2} gauge (586 kPag). Only during idle descent did bleed air pressure drop to the 50 lbf in^{-2} gauge (345 kPag) level, which would have negated replenishment of the BOS, had it been required. The bleed air temperature at the concentrator inlet typically cycled between 20 and 40 °C. The temperature fluctuation shifted up or down somewhat with altitude, but had no effect on concentrator performance. The YA-7F test program was completed in 1991. No production aircraft were built.

F-15E STRIKE EAGLE MOLECULAR SIEVE OXYGEN GENERATING SYSTEM

Introduction

In the late 1980's the USAF developed the F-15E "Strike Eagle", a two-seat, dual-role, integrated fighter for all-weather, air-to-air and deep interdiction missions. In addition to new engines and significant upgrades to the crew stations, the F-15E was equipped with an onboard oxygen generating system. A seat-mounted gaseous oxygen bottle was retained for emergency use in the event of system failure or ejection.

System Description

The MSOGS is a replacement for the conventional LOX convertor. The F-15E MSOGS supplies oxygen-enriched breathing gas to an air-mix regulator which has been adjusted to accept an MSOGS product gas mixture containing 93-95% oxygen instead of 99.5% oxygen which would normally be provided by a LOX convertor. The MSOGS concen-

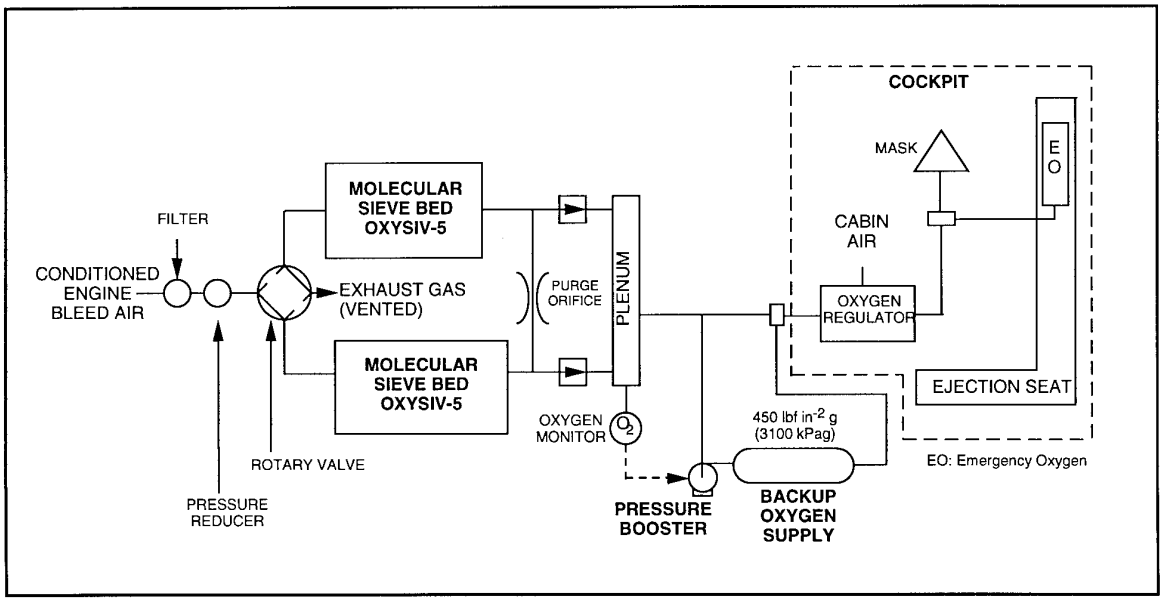

Fig. 8.22 Simplified flow schematic for the F-15E molecular sieve oxygen generating system. Only one crew position and regulator shown.

trator is similar to the MSOC fitted to the AV-8B Harrier, but improved to increase reliability and maintainability. The improvements include (a) a zirconium oxygen sensor and microprocessor to control the MSOGS, and (b) an integral self-charging (to 450 lbf in^{-2} gauge) (3,100 kPag) backup oxygen supply (BOS) capable of providing 20 man-minutes (at sea level) of 93% oxygen enriched breathing gas in the event of a failure of the supply of gas by the concentrator, or for ground operation with engines off.

The MSOGS for the F-15E aircraft was developed by Litton as contractor-furnished equipment for McDonnell-Douglas Aircraft Corporation. The F-15E MSOG system (Figure 8.22) consists of a concentrator, pressure booster, oxygen concentration monitor/controller, backup oxygen supply, regulator, and anti-G valve (23).

Molecular Sieve Oxygen Concentrator

The major components of the molecular sieve oxygen concentrator are two adsorbent cylinders containing OXYSIV-5 zeolite, a rotary (inlet) valve, dual piston oxygen compressor, 3-way product select valve, BOS storage plenum containing 5AMG zeolite molecular sieve, and a monitor/controller. The air source is engine bleed air which is withdrawn from the aircraft environmental control system downstream of the water separator. Conditioned bleed air enters the concentrator and passes through the MSOGS coalescing filter, which removes particles and water droplets.

Product gas from the concentrator flows to the pressure booster for charging of the molecular sieve-filled BOS and to the two crewmember stations via the concentrator 3-way outlet valve. Whenever the oxygen concentration of the product gas is 93 percent or above, and the concentrator inlet pressure is sufficient to charge the BOS, the booster shut-off valve opens, starting the pressure booster operation. The booster is driven by pressurized air extracted downstream of the concentrator rotary valve. When the BOS pressure reaches its maximum value of 450 lbf in^{-2} gauge (3,100 kPag), the pressure booster is shut off automatically. A 500 lbf in^{-2} gauge (3,450 kPag) relief valve and a 600 lbf in^{-2} gauge (4,140 kPag) burst disc protect the BOS from overpressurization.

Regulation and Control

All concentrator functions are controlled by the monitor/controller mounted on the concentrator. The monitor/controller unit consists of a zirconium solid state oxygen sensor, absolute pressure regulator, control solenoid valves, pressure transducers, and electronics control circuitry. The monitor/controller measures the oxygen concentration of the product gas, and activates a caution signal and test indicators, when appropriate. It also controls the backup oxygen fill operation as well as the 3-way valve operation. The monitor/controller checks for both critical and non-critical types of failures. Critical failures include (a) low partial pressure of oxygen, (b) low concentrator outlet pressure, and (c) failure of the pressure transducer and/or oxygen sensor. Whenever a critical failure is detected, the MSOGS unit will activate the caution light, switch to BOS breathing gas, and trip the concentrator test indicators. Non-critical failures include (a) pressure reducer fault, (b) pressure transducer fault, (c) BOS fault, (d) inlet filter failure, and (e) open failure of the concentrator inlet valve. When a non-critical failure is detected, the MSOGS unit will trip the appropriate test indicators, but will not illuminate the caution light.

After the oxygen-enriched product gas leaves the concentrator, it is routed to the forward and aft crewstation console-mounted breathing regulators. The MSOGS regulator, designated CRU-98/A is similar to the standard CRU-73/A LOX regulator, but modified for lower pressure operation (down to 20 lbf in^{-2} gauge) (138 kPag) and to provide positive pressure breathing as a function of G-force (PBG). The PBG function is controlled by the PBG position on the oxygen regulator ON/OFF/PBG switch. The PBG position is normally locked out to prevent inadvertent selection of PBG without the proper crew-side equipment (counter-pressure vest). The regulator is of the air dilution type with entrainment of air controlled by an aneroid in accordance with cabin altitude. At a cabin altitude of approximately 25,000 feet, the air inlet port is completely closed, and the regulator outlet is supplied with 100% MSOGS product gas. The CRU-98/A regulator also incorporates a compensated dump valve to limit the maximum breathing pressure to 18 mm Hg (2.4 kPag) when no altitude or G-modulated pressure breathing is required. A low-pressure relief valve limits the maximum outlet pressure to 50 mm Hg (6.7 kPag)for altitude protection, and a high-pressure relief valve limits the maximum outlet pressure to 80 mm Hg (10.7 kPag)when G-compensated pressure breathing is provided.

Performance Testing and Man-Rating

Performance testing and man-rating of the F-15E MSOGS was accomplished at the Armstrong Laboratory in 1990-91 (18). Unmanned functional testing of the MSOG components (oxygen concentrator, compressor, regulator, and backup oxygen supply), and subsystems was followed by a comprehensive manned test program which ensured that the MSOGS would perform according to design in all phases of flight. The manned protocol included altitude and acceleration testing, positive pressure breathing, and rapid decompression. In all laboratory tests, The F-15E MSOGS demonstrated that it could adequately protect the two F-15E crew wearing standard flight equipment to an altitude of 50,000 feet under normal and virtually all forseeable emergency situations. The MSOG system operated satisfactorily at the minimum specified oxygen concentrator inlet pressure of 30 lbf in^{-2} g (207 kPag), which produced a regulator inlet pressure of 20 lbf in^{-2} g (138 kPag). The F-15E MSOG system provided positive pressure breathing for G-protection (PBG) to +9 Gz using Combat Edge equipment within safe physiological limits. Flight testing of the MSOGS-equipped F-15E was performed in 1991 at the Air Force Flight Test Center, and demonstrated that the MSOGS was compatible with the mission of the F-15E dual role fighter (17).

Production installation of the MSOGS in the F-15E was initiated in August 1991, at about the mid-point in the aircraft production run. Kits for retrofit of the remaining aircraft were developed, and, as of late 1995, nearly the entire active duty fleet of 138 aircraft has been equipped with MSOGS. In the three-year operational experience, no significant problems have been reported.

MOLECULAR SIEVE OXYGEN CONCENTRATION SYSTEM FOR THE UK EXPERIMENTAL AIRCRAFT DEMONSTRATOR PROGRAMME (EAP)

Introduction

A molecular sieve oxygen concentrator (MSOC) system was installed in the United Kingdom Experimental Aircraft Programme (EAP) demonstration aircraft in 1990 when the work performed on this aircraft became a part of the development programme in support of the European Fighter Aircraft (now Eurofighter 2000) being developed by Germany, Italy, Spain and the United Kingdom. The MSOC system for the EAP aircraft was designed and tested in ground rigs and in flight, by the Military Aircraft Division of British Aerospace, employing prototypes of the components being developed by industry for the European Fighter Aircraft (EFA). The ground and flight test programme yielded valuable information which has been employed in the design of the MSOC system for Eurofighter 2000.

System Description

The MSOC system installed in the EAP aircraft comprised a supply of conditioned bleed air, an oxygen concentrator, zirconia and galvanic oxygen sensors, a type 600 regulator package (with a pressure breathing with G (PBG) module), a personal equipment connector, type P/Q mask and chest counterpressure garment, and a seat mounted emergency oxygen supply. The LOX converter which had already been installed in the aircraft provided a backup supply of oxygen. The air supply to the MSOC was taken from the Environmental Control System and passed through a heat exchanger which cooled it to between 0° and 40°C, and a water extractor. The cooled air then flowed through a combined reducing and relief valve which controlled the pressure of the air delivered to the MSOC to 18-44 lbf $in^{-2}g$ (125 - 310 kPag) and a plenum to the inlet of the oxygen concentrator.

Molecular Sieve Oxygen Concentrator

The lightweight oxygen concentrator manufactured by Normalair-Garrett Ltd was cylindrical in shape (18 cm diameter and 53 cm long) and comprised three concentric beds of molecular sieve (Figure 8.23). The air supply to, and the

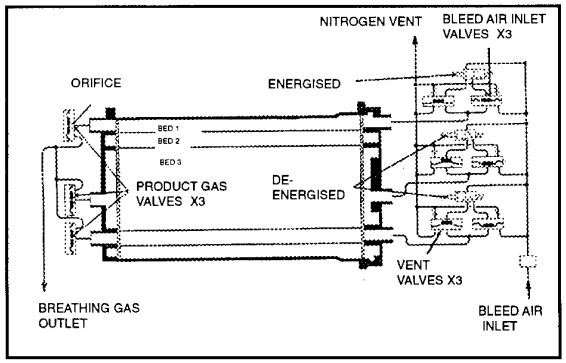

Fig. 8.23 Lightweight oxygen concentrator developed by Normal-Garrett Ltd for the UK Experimental Aircraft Demonstrator Programme (EAP).

venting of gas from, each bed was by way of a pair of servo operated diaphragm valves, operation of which was controlled by a solenoid. Product gas, a fraction of which was used to purge another bed, finally passed through a non-return valve into a plenum. The sequence of operation of the solenoid valves was controlled by the aircraft Utilities System Management System (USMS). The cycle time of the concentrator was varied in 1 second steps between 9 and 30 seconds, a faster cycle time giving a higher concentration of oxygen in the product gas. The USMS selected the appropriate cycle time in response to the output of the zirconia sensor and cabin altitude, to maintain the concentration of oxygen in the product gas within the limits of the specification which were very similar to those given in Figure 5.3 of Chapter 5. The design line for the control of oxygen concentration by the USMS increased linearly with altitude from 40% at ground level to 50% at 15,000 feet and then to 94% at 30,000 feet.

The health and performance of the MSOC was continuously monitored by the USMS which checked that the concentration of oxygen in the product gas in relation to cabin altitude was within specification limits. A built-in-test on the ground ran the MSOC at the fast cycle time and checked that the concentrator produced gas having the maximum concentration of oxygen.

Oxygen Sensors

Two oxygen sensors employing different technologies were used to monitor the concentration of oxygen in the product gas. The concentration of oxygen in the product gas flowing from the MSOC was measured by means of a zirconia oxygen monitor which was also supplied with reference air from a tapping upstream of the MSOC. This sensor consisted of a platinum coated zirconia disc mounted in a small cavity, the temperature within which was held around 725°C. Product gas and reference air were supplied to either side of the zirconia disc and the potential difference created by a difference in oxygen concentration was sensed and amplified. The output of the zirconia sensor was transmitted to the USMS where the signal was used to determine, in relation to cabin altitude, the cycle speed of the oxygen concentrator, thus providing closed loop control of the concentration of oxygen. The USMS also continuously monitored whether the concentration of oxygen in the product gas, as indicated by the zirconia oxygen sensor, fell below the minimum specified for the prevailing cabin altitude [a PO_2 of 175 mm Hg]. In the event of the oxygen concentration falling below the minimum acceptable level, the USMS selected the backup oxygen supply and illuminated an AMBER warning. If the backup oxygen supply was not selected, then a RED warning was illuminated. Directly the concentration of oxygen in the product gas increased above the minimum acceptable level, the backup oxygen supply was deselected and the AMBER warning occulted.

The second oxygen sensor, which had a limited performance, comprised a galvanic cell the output of which was determined by the partial pressure of oxygen (PO_2) in the product gas. The galvanic PO_2 was mounted in the pressure cabin and a small bleed of product gas passed through the cell at the absolute pressure within the pressure cabin. The output of the galvanic PO_2 sensor operated a Red warning when the PO_2 of the product gas fell below 175 mm Hg, thus providing an independent monitor of the adequacy of

the concentration of oxygen in the product gas.

Backup Oxygen Supply

The gaseous oxygen from the LOX converter already fitted to the aircraft provided the source of backup oxygen in the event of a malfunction of the MSOC system. The gaseous oxygen was led into the product gas pipework immediately downstream of a non-return valve through an on/off valve. The backup gaseous oxygen supply at a pressure of 85 lbf $in^{-2}g$ (586 kPag) could be selected automatically by the USMS on detecting a failure of the MSOC system, automatically by an aneroid when the cabin altitude exceeded 25,000 feet, and manually by the pilot.

Demand Regulator and Personal Equipment Connector

The product gas was carried through the seat mounted personal equipment connector to a modified type 600 demand regulator package. The basic type 600 dual demand regulator package was that employed in the MSOC system of the RAF Harrier GR5 aircraft which is described in the third section of this chapter. The modification to the type 600 regulator package employed in the EAP aircraft was the addition of a Pressure Breathing with $+G_z$ accleration (PBG) module. The main regulator with the PBG module provided pressure breathing in response to a pressure signal from the G trouser port of the personal equipment connector. The performance of the PBG module in relation to the anti G valve fitted to the aircraft was such that pressure breathing commenced at 2G and increased linearly with $+G_z$ acceleration to 60 mm Hg (8.7 kPa) at 9G.

Emergency Oxygen System

A standard 70 L (NTP) capacity emergency oxygen bottle with an on/off and reducing valve assembly was mounted on the ejection seat. The outlet of the emergency oxygen assembly was connected to the product gas supply port in the personal equipment connector. The emergency oxygen supply could be selected manually by the pilot, and was selected automatically on ejection.

Personal Equipment

Product gas was carried through a hose assembly from the personal equipment connector to a type P/Q mask. The bladder of the chest counterpressure garment, when it was worn, was connected into this hose assembly. The pilot wore an early standard of the UK full coverage anti G trousers.

Ground Rig Tests

Extensive tests of the performance of parts and the whole of the EAP MSOC system were performed in a hypobaric chamber. The effect of changes in the pressure and temperature of the air supplied to the MSOC, of the temperature of the MSOC, and of changes in altitude and steady flow and cyclic demands upon the performance of the system were determined. The effects of failures of various components were also studied. The performance of the system was found to be very satisfactory, with the concentration of oxygen being controlled within the limits of the specification. The only situation in which the oxygen concentration went outside the limits was on very fast climb and descent. These deviations were due to inadequate responsiveness of the system. There was, however, warning of a low oxygen concentration and automatic selection of the backup oxygen supply.

Flight Trials

Following successful completion of the ground rig tests, the MSOC system was installed in the EAP demonstrator aircraft with extensive instrumentation to record the behaviour of the system in flight. It provided breathing gas to the pilot in a total of 13 flights which covered much of the flight envelope of the aircraft. The performance of the MSOC system was very satisfactory. There were a series of AMBER warnings, all of which cleared in a few seconds, which were due principally to the period in the oxygen concentration smoothing routine being too short to remove very transient spikes of low concentration. The pilots found the system to be fully acceptable except for the transient AMBER warnings and the presence of safety pressure at low altitude.

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Chapter 9

SENSORS, INDICATORS AND CONTROLS IN ADVANCED OXYGEN SYTSTEMS

John B. Bomar, Jr.

INTRODUCTION

The advent of the onboard oxygen generating system (OBOGS) has stimulated a reassessment of sensors, indicators and controls used in military aircraft oxygen systems. The purpose of this chapter is to present a rationale for the design of instrumentation and controls for Advanced Oxygen Systems (AOSs) with onboard molecular sieve oxygen generation systems (MSOGS). Fundamentally, the guiding philosophy for the choice of sensors and indicators should be the same for any aircraft oxygen system. The cockpit displays should have clear symbology indicating the status of the oxygen system and should enable the operator to correctly diagnose and rectify system faults. In this regard, an AOS with an MSOGS breathing gas source is no different from conventional oxygen systems. Thus, a review of the instrumentation and controls for a conventional aircraft oxygen system is useful to illustrate current principles and practice. With this as a basis, the rationale for sensors, indicators and controls in MSOGS is developed by discussing the potential failure modes in a typical MSOGS based AOS. Finally, a method is suggested for developing in-flight procedures for MSOGS through simplified failure mode analysis.

CURRENT PRACTICE

The following description of the oxygen system of the USAF F-16A illustrates current practice in the design of instrumentation and controls for conventional oxygen systems in modern military aircraft. The source of breathing gas for the F-16 oxygen system consists of a LOX (liquid oxygen) supply for normal use and a gaseous system for emergency use. A schematic of the complete system is given in Figure 9.1. A five liter LOX converter supplies breathing oxygen to a pressure demand, air dilution regulator. The regulator's controls allow the selection of normal diluted oxygen, 100 percent oxygen and safety pressure [4-6 inch water gauge] (1-1.5 kPag) emergency oxygen (not to be confused with the bailout oxygen supply system). The bailout oxygen system consists of a high pressure (1800 lbf in^{-2} g) (12,400 kPag) bottle and pressure reducer mounted on the ejection seat. This system is actuated automatically on ejection, or manually, by pulling a ring and cable arrangement.

Most of the oxygen system indicators are grouped on the same panel with the other critical systems caution and status indicators. There are indicators for oxygen flow, LOX quantity, and cabin pressure altitude. A second oxygen flow indicator is built into the regulator face. An OXY LOW caution light indicates low system pressure or low LOX quantity (less than 0.5 liter). When activated, the OXY LOW indicator causes the illumination of the MASTER CAUTION light. The oxygen system pressure can be read from a gauge incorporated in the face of the demand regulator. Regulator controls include the SUPPLY ON/OFF, dilution NOR-

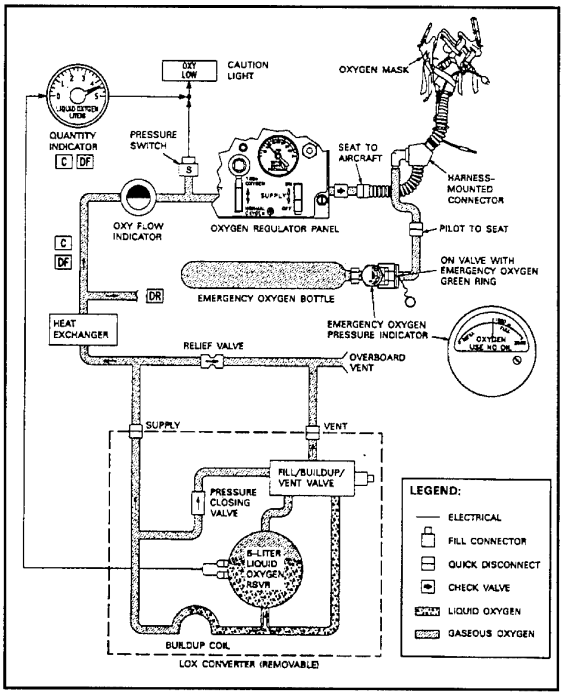

Fig. 9.1 Schematic of aviator's breathing oxygen system for F-16A using standard liquid oxygen supply.

MAL/100% and the EMERGENCY/TEST MASK lever. A test switch may be used to check the function of the OXY LOW caution light. When activated, the switch causes the oxygen quantity gauge to display a decreasing volume of oxygen. When the quantity gauge indicates less than 0.5 liter the MASTER CAUTION and OXY LOW indicators are illuminated. The physical sensors for the indicators and warning system are based on old, but proven technology. The oxygen quantity sensor is the capacitance type commonly employed in other LOX converter based systems. Oxygen flow is sensed by a mechanical flow sensor and transmitter. A "blinker" indicates flow in the cockpit with an alternating black and white display. The oxygen low pressure sensor is a simple pressure activated switch.

The philosophy behind the F-16 oxygen system sensors, indicators and controls is based on providing the pilot information about the quantity and integrity of the oxygen supply and the status of the oxygen pressure and flow regulation equipment. Control of the system is by manual activation of either mechanical or pneumatic devices. Automatic control is used only for oxygen dilution, pressure relief and activation of the emergency bailout oxygen supply on ejection.

The F-16 oxygen system is typical of oxygen systems in other tactical fighter and primary jet trainer aircraft, with the exception that the latter usually use medium pressure gaseous supplies rather than LOX. Oxygen systems for cargo and troop transport aircraft are used as a backup to a

high differential cabin pressurization system that maintains the pressure cabin at altitudes below 10,000 feet. They usually have a much larger source of LOX, but the sensing, indicators and controls are the same as in the other systems. Strategic bombers typically employ high differential pressurization systems and large LOX supplies as with cargo aircraft, but the oxygen system is used more often during flight especially during hazardous mission phases.

Ideally, the controls and indicators of the AOS should be analogous to those of the LOX based system. However, because the MSOGS employs substantially different technology in producing breathing gas, the sensing, fault detection, indicators and controls are by necessity somewhat different than those of non-MSOGS systems.

POTENTIAL FAILURES IN MSOGS

A review of the potential failures of an MSOGS will help develop the rationale for providing specific sensors, indicators and controls for an AOS. Most failures fall into three general classes: (a) failure of the compressed air source; (b) failures of the oxygen concentrator including loss of electrical power supplies; and (c) failures of the product gas distribution system. Marginal operating conditions, emergency and standby modes, while not failures, constitute a fourth class of conditions requiring sensors, indicators and controls beyond those required for fault detection and diagnosis.

Compressed Air Source

Failures of the air supply to the MSOGS divide into loss of the source of supply (typically as a result of engine failure) and failure of the conditioning system controlling the temperature, pressure and humidity of the compressed air supply. In the former, the MSOGS product gas flow rapidly ceases as the concentrator outlet pressure approaches the inlet pressure (usually the absolute pressure at aircraft ambient altitude). The effects of partial blockage (reduced pressure) of the air supply are the same as low supply air pressure occurring "normally" in some aircraft at low engine power settings.

Failure of the conditioning system may lead to increased inlet air temperature, or pressure or both, as well as high humidity or even liquid water in the inlet air stream. Inlet pressures higher than the concentrator relief valve pressure will cause vent flow from the concentrator. The pressure within the concentrator as well as the product pressure will be regulated by the internal pressure regulating valve within the concentrator. However, if the mass flow through the supply pipework exceeds the capacity of upstream heat exchangers to cool the air supply, overheating of the concentrator can occur. Partial or complete failure of upstream cooling may also result in overheating of the concentrator. As concentrator temperatures rise above approximately 70°C, the efficiency the concentrator will decline and at temperatures above 120°C, the concentrator will essentially fail to function as an air separation device. The product temperature may rise at the concentrator outlet, but breathing gas temperature usually does not rise substantially as the residual heat is typically conducted into the airframe through the walls of the pipework.

Because most of the contaminants reaching the molecular sieve beds are ejected from the beds during the purge cycle, as long as the concentrator is cycling, failures, or engine ingestion, leading to gross contamination of the inlet air stream with water vapor, aerosol or even liquid water are of little immediate importance. However, gross contamination of the air supply with liquid petroleum products and dirt or dust may lead to partial or complete blockage of the inlet air filter and thereby compromise the concentrator air supply. The effects of contamination of supply air with common engine bleed air contaminants and chemical warfare agents are discussed in detail in Chapter 11.

As discussed above, failures of the compressed air supply or conditioning system will usually lead to one of two conditions: (a) low concentrator outlet pressures, with consequent breathing gas regulator starvation and lowered product gas oxygen concentration; or (b) concentrator failures secondary to high inlet air temperatures.

Concentrator Failures

The most serious failure of the concentrator proper is failure of the mechanism controlling the pressure swing cycle. As explained in Chapter 6, the difference in charging and outlet pressures provides the energy for the air separation. Any reduction of the pressure swing or purging flows leads to reduced concentrator efficiency and poor air separation. The concentrator failures which can lead to loss of pressure swing or purge cycles are MSOGS design specific and will not be discussed here in detail. Generally, loss of electrical power, inlet air pressure, or failure of pneumatic or electrical devices which time and direct the charging and purging flows will lead to degradation of the air separation process and lowered product oxygen concentration. Two bed systems are vulnerable to loss of pressure cycling or purge flows. Systems with three or more beds can typically continue to provide some air separation when as few as two beds are working. However, the efficiency is usually degraded to a much higher degree than one would suspect because the loss of oxygen rich product and purge gases from the failed beds dilutes the product gas and reduces the purge efficiency.

The effect of loss of pressure cycling on concentrator outlet pressure is dependent on the concentrator design and mode of failure. The concentrator outlet pressure may fall to ambient or be within the normal range depending on the MSOGS design and the type of failure. Some designs are susceptible to degradation of the molecular sieve if the pressure cycle is interrupted and flow through a bed occurs for more than a few minutes. It is always prudent to assume the molecular sieve may have been contaminated whenever a concentrator failure affects the pressure swing charging or purging cycles.

Any contamination of the molecular sieve material may "deactivate" its nitrogen adsorbing capacity and lead to reduced air separation. Molecular sieve will rarely become deactivated during any routine operations (see Chapter 11). However, prolonged storage in humid atmospheres or in industrial areas where the air may be contaminated with organic vapors may lead to deactivation of the molecular sieve within the concentrator if the inlet and outlet ports are not sealed against the environment. The consequence of deactivated molecular sieve is reduced product oxygen enrichment, usually with no other signs of failure.

Failures due to low temperature are rare and are usually seen only on start-up after a "cold soak." Jet engine bleed air is usually warm, if not hot, and thermal problems with oxygen concentrators are usually associated with overheating as discussed above. Nevertheless, in cold, humid conditions, ice may temporarily block inlet pressure regulation and filtration devices within the concentrator. Once the concentrator is warmed, either by internal inlet air heaters or by warm inlet air, there are no further problems with low temperature. Cold temperatures on start up may transiently reduce the air separation efficiency of the molecular sieve in the concentrator beds for a few minutes. For the AV-8A system, normal efficiency is reached after approximately 10 to 15 minutes (2).

Partial blockage of the exhaust port from the concentrator will cause lowered concentrator efficiency for the same reasons as loss of inlet pressure. This is because the pressure swing during the charge and purge cycles is reduced. Blockage of the concentrator exhaust outlet pipework is typically caused by foreign objects becoming lodged inside the pipework. There is even one report of an exhaust port being blocked by a wasp nest! Prevention by screening the exhaust outlet is effective.

Other concentrator failures include outboard leaks from the product pipework or reversed flow of product gas through failed check valves. Both of these failures lower the concentrator outlet pressure, and depending on the severity, an outboard leak may cause the product oxygen concentration to fall below 30%. Failure of internal inlet pressure regulation may cause internal and product outlet pressures to track fluctuations in supply pressures to values above the normal operating pressures for the beds. If external supply pressure regulation is provided in the system, the failure of internal pressure regulation valves will be "dormant" until the external regulating device fails. The concentrator is typically protected against high internal pressures by a relief valve. The consequences of high flow through the relief valve were discussed above.

Inlet air flow channeling around or through the molecular sieve material may be caused by deterioration or failure of internal seals (possibly induced by extremes of temperature) or, rarely, by loose packing of the molecular sieve material. Channeling or bypass air flow will cause reduced air enrichment to the extent of the short circuit flow. The effects of internal seal failures are specific to the concentrator bed design and no general conclusions from such failures are possible. Loss of the molecular sieve material from the beds or under filling of the beds can result in loose packing of the remaining material and flow channeling or short circuit flow from bed inlet to outlet. Loosely packed beds are susceptible to vibration induced attrition of the clay binder matrix in the molecular sieve material with resulting dust generation, contamination and possible failure of internal and downstream flow and pressure regulation devices.

Thus, concentrator failures lead to: (a) low product oxygen partial pressure with risk of hypoxia at altitude; (b) lower product pressure; and/or (c) inadequate flow capacity and breathing regulator starvation.

PRODUCT DISTRIBUTION SYSTEM

The discussion of distribution system faults or failures in this section will be limited to those within the components designed to confine, conduct, and regulate the pressure and flow of product gas from the MSOGS. System faults associated with sensors, indicators and controls will be deferred to the section where those devices are described. At a minimum, the distribution system of an MSOGS consists of a length of medium pressure pipework leading to the inlet of a demand breathing regulator which, in turn, feeds a length of low pressure oxygen hose (and perhaps an oxygen sensor), through one or more connectors to the inspiratory valve of an oronasal "oxygen" mask. Some means of supplying an alternate source of breathing gas will also be present. Typically, a selector valve upstream of the demand regulator switches the source of the regulator supply to standby breathing gas (typically 100% oxygen) or a pressure regulated emergency supply of oxygen supplied directly into the low pressure oxygen hose through a connector. In many systems, both standby and emergency systems are present to cope with in-flight MSOGS failures and ejection, respectively. Failures of these components are discussed below.

Medium Pressure Pipework.

The oxygen concentrator is typically mounted outside the pressure cabin in tactical aircraft, but may be mounted within the pressure cabin in larger aircraft such as transport, cargo or strategic bombers. The most significant failure of the medium pressure pipework is leakage. Under "normal" operating conditions small leaks are inconsequential. However, in conditions where the concentrator performance is marginal, even small outboard leaks (ca. 5 L [STP] min^{-1}) can significantly lower product oxygen concentration by superimposing a parasitic flow demand on the system. Partial or complete blockage of the medium pressure pipework circuit will manifest itself as an abnormally high pressure loss with concomitant regulator starvation at higher demand flows.

Demand regulator.

The common failures of demand breathing regulators are well known and they all apply in MSOGS. Demand valve failures leading to blocked flow or full flow must be accommodated by providing an alternate source of breathing gas for the former and immediate pressure relief in the latter. An alternate source of breathing gas (with separate regulation)is required in a full flow failure as the oxygen concentration of the product gas falls below the proper level (see Chapter 5). Most regulators designed for MSOGS are designed to operate at "low inlet pressure" - as low as 2-5 lbf in^{-2} g (14-34 kPag). Depending on the design, these low inlet pressure regulators may not be as tolerant to "high inlet pressure" [P > 100 lbf in^{-2} g (690 kPag)]. Thus, if a pressure regulation failure occurs in the upstream pipework, the regulator may not work properly.

Low Pressure Pipework.

The most common failures of the low pressure pipework system (including the oronasal mask) are leakage and inadvertent disconnection from the oxygen system. Leakage from the low pressure circuit may be inboard or outboard depending on the phase and depth of breathing and the regulator design. Inboard leaks may occur during heavy breathing if the pressure in the low pressure pipework drops below

ambient. The major consequences of significant inboard leaks include dilution of breathing gas with a potential for hypoxia at altitude and contamination of breathing gas with smoke or fumes should a cockpit fire occur. Outboard leaks are typical of systems employing "safety pressure." Regulators supplying gas at an inch of water gauge (0.25 kPag) or so above ambient are commonly employed in MSOGS. A poor mask seal or a pipework defect in the presence of safety pressure, will cause an outboard leak. If the mask is removed from the face, a regulator with safety pressure will typically flow more than 100 L [STP] min^{-1} of product gas. Depending on the capacity of the concentrator, this flow may be enough to reduce the product oxygen concentration well below the desired value.

Thus, the effects of distribution system failures are sometimes similar to those seen in conventional oxygen systems. Inboard leaks may lead to hypoxia at altitude and regulator failures may result in no flow or full flow of breathing gas. Outboard leaks are more serious in MSOG systems. The effect of outboard leakage is low product oxygen partial pressure or premature depletion of the backup oxygen supply. Preflight system integrity checks are essential.

STANDBY AND EMERGENCY OPERATION

Standby and emergency modes make up a class of operating conditions requiring unique sensors and indicators. The terms "standby" and "backup" have been employed interchangeably to indicate a mode where the source of breathing gas was the alternate supply of gaseous oxygen carried in case of concentrator failure or decompression. Here, the term "standby" will mean a non-emergency situation where the aircraft engines are not running and the term "backup mode" will refer to an emergency change of the breathing gas source to a backup oxygen supply (usually gaseous oxygen).

Standby Operation.

Standby modes were first considered for MSOGS with methods to give nuclear biological chemical warfare (NBC) protection of aircrews. Clearly, the preferred solution to the ground standby scenario is to provide gas via an auxiliary power unit (APU) while the aircraft is on the ground with engine(s) off. Indeed, modern tactical fighters such as the Eurofighter 2000 and the F-22 have APUs on the aircraft. Nevertheless, there are many currently operational aircraft without APU air supplies on which a supply of breathing gas must be provided.

In the NBC scenario, the crewmember requires a source of clean breathing gas before engine start. In fact, this requirement exists in the non-NBC situation, as well, but it has been assumed the crew could breathe ambient air until the engines were started. This assumption is questionable. (See Chapter 10). Sensors and indicators in the MSOGS should inform the crew of the source of breathing gas. If an ambient air bypass valve is employed, the cockpit displays should indicate to the pilot when the valve is open. If inward relief valves are employed, an unambiguous signal should be given to the crewmember to notify him of the opening of the valve. This may take the form of high inward breathing resistance compared to the resistance experienced when the MSOGS concentrator is on-line. System sensors should detect the passage of the cabin pressure altitude through 10,000 feet and either inform the crew of the ensuing hypoxia hazard, or signal the controls to automatically switch the source of breathing gas from cabin ambient air to either the concentrator or the backup oxygen supply. The crew must be informed of the change in the source of breathing gas through an indicator or breathing resistance change.

Emergency Modes.

Emergencies are by definition initiated by non-routine events. Most of the MSOGS failures discussed above lead to use of the backup breathing gas supply. This supply usually provides no more than thirty minutes breathing time to let the crew either rectify the fault and continue the mission, or safely descend to a low altitude where the oxygen system is not required.

Besides the MSOGS failures already discussed, loss of cabin pressurization at altitude must be considered. Aircraft cabin pressurization is obtained by regulating the outflow from the pressure cabin of a conditioned air supply taken from the engine(s). In single engine aircraft, engine failure (flameout) always results in an eventual loss of cabin pressurization (and, usually, MSOGS supply air). In multi-engine aircraft, cabin pressurization may be adequate during single engine failure, but multiple engine failure will usually result in a decrease of the bleed air distribution system pressure. Two other engine conditions may degrade cabin pressurization: (a) engine intake compressor starvation at high altitude; and (b) throttle retardation leading to low engine power output. In these conditions, cabin pressure altitude may rise toward ambient aircraft pressure altitude. Other cabin pressurization failures may be caused by: (a) rupture of the pressure cabin or failure of canopy or door pressure seals; (b) failure of the environmental control system; (c) pressurization dump valve failures; or (d) the crew may dump the cabin pressure to purge toxic smoke, fumes or gases from the cockpit.

MSOG systems supply gas with an adequate oxygen partial pressure for the crew whenever the cabin pressurization system is operating normally. However, failure of the cabin pressurization system while the aircraft is in flight, will usually require the source of breathing gas to be switched from the MSOGS concentrator to the backup oxygen supply. In slow cabin decompression, the oxygen concentrator may produce an adequate product oxygen concentration so that no switch to the backup supply of oxygen is required. In rapid decompression, the rate of rise in product oxygen partial pressure will lag the decompression event sufficiently to require a switch to backup breathing gas. In explosive decompression caused by catastrophic loss of the integrity of the pressure cabin, breathing gas with a high oxygen concentration must be delivered to the crew within one breath to prevent transient hypoxia (see Chapter 5).

Thus, standby and emergency operating conditions require source indication and rapid selection of alternate sources of breathing gas. The sensor, indicator and control system must warn the crew of cabin decompression and allow a rapid change to the backup oxygen supply should decompression occur.

AOS SENSORS AND INDICATORS

This section draws on the discussion above to present a rationale for choosing the sensors and indicators for an MSOGS based AOS. As stated previously, the cockpit displays should have clear symbology indicating the status of the oxygen system and should enable the operator to correctly diagnose and rectify system faults. The classification of cockpit indicators used here is that specified in NATO STANAG 3370 (1). This STANAG groups indicator signals into three classes: (a) Warning; (b) Caution; and (c) Advisory, as follows:

a. Warning Signal:

(i) A signal indicating the existence of an imminent catastrophic condition requiring immediate action or a limitation to the flight envelope of the aircraft.
(ii) A Master warning signal may be used to indicate operation of any one of a number of warning signals.

b. Caution Signal:

(i) A signal indicating the existence of a hazardous or impending hazardous condition requiring attention but not necessarily immediate action.
(ii) A master caution signal may be used to indicate operation of any one of a number of caution signals.

c. Advisory Signal:

A signal used to indicate aircraft configuration, a condition of performance, the operation of essential equipment, or to attract attention for routine purposes.

AOS Warning Signals

MSOGS failures leading to inadequate oxygen partial pressure in the breathing gas may lead to incapacitating hypoxia in the crew. Such failures require "immediate action" to prevent "an imminent catastrophe" or a "limitation of the flight envelope of the aircraft." In conventional oxygen systems, low oxygen quantity or supply pressure are indicated by an OXY LOW warning. Abnormal flow conditions are indicated by the oxygen flow indicator or difficulty in breathing. In an MSOGS, concentrator, failures may lead low oxygen partial pressure in the breathing gas while all other indicators are signaling normal operation. The only way to detect such a failure is by sensing the oxygen partial pressure of the concentrator product gas.

The current concepts for advanced oxygen systems show an oxygen sensor is likely to play a central role in the overall function and reliability of the system. Oxygen sensor technology and the practical problems associated with oxygen sensing are discussed in Chapter 10. At a minimum, an oxygen sensor for warning of low oxygen partial pressure is essential for an AOS. The logical indicator caption to employ is an OXY LOW caption such as used in the F-16. The central warning caption and audio warning tone should be activated simultaneously. The interpretation of the warning is different, but the crew action is the same, *i.e.* select backup or emergency oxygen supply.

AOS Caution Signals

All significant AOS failures will ultimately activate the OXY LOW warning if the warning level is set above sea level ambient oxygen partial pressure (ca. 160 mm Hg). However, there is little point in activating the warning system if the causative faults can be detected before the warning condition occurs. Three failures are easily detected to allow warning the crew of "an impending hazardous condition..." are: (a) low product delivery pressure; (b) outboard leakage of product gas; and (c) high bleed air or concentrator temperature. A fourth condition requiring a cautionary signal is a low quantity of backup oxygen supply.

The sensors required detect the first two failures are a product line pressure switch and a product flow sensor, respectively. Sluggish flow in conjunction with high breathing resistance (breathing difficulty on inspiration) could be used to deduce low product pressure. However, a flow sensor alone cannot be used to distinguish between low system supply pressure and line blockage or severe outboard leak (upstream of the flow sensor) with resulting low product pressure. The product flow and low system pressure indicators are already present in conventional oxygen systems such as the F-16, so they map naturally to an AOS, although their interpretation is somewhat different.

High bleed air temperature may be detected with a concentrator inlet air temperature sensor (thermistor). The high temperature sensor may cause illumination of a separate caution caption or the OXY LOW warning caption. The former is preferable even though it adds another indicator caption, because the high temperature condition may not result in low oxygen partial pressure until the concentrator temperature has risen to a very high value. The period between the causative failure and loss of air enrichment in the concentrator may be as long as an hour. Backup selection would be inappropriate until the low oxygen partial pressure warning caption is illuminated. A thermistor could be located within the concentrator, but there is usually no single site where the temperature represents the effective operating temperature. Moreover, the inlet air temperature sensor gives a caution signal before the actual hazardous condition occurs.

A caution signal is required if the quantity of backup breathing gas falls to a level where further depletion can lead to a hazardous condition or limit the flight envelope. If the backup supply is not generated onboard, this caution should be illuminated whenever backup is selected. A backup oxygen quantity indicator displays an estimate of the remaining supply of backup gas. It could be adequate simply to provide a warning when the backup oxygen system contents drop to a level which is just adequate for aircraft descent or ejection at a safe altitude; e.g., 70 liter (NTP). If, however, the backup supply is generated on board, a simple low pressure switch might suffice.

AOS Advisory Signals

AOS advisory indicators should advise the crew of the mode of operation of the MSOGS and the quantity of backup oxygen supply available. The system mode may be indicated by an illuminated caption or the position of the mode selector or both. Care should be taken in the design of the mode selector and indicator to ensure an unambiguous relationship between the two. If backup oxygen selection is made auto-

matically (e.g. on cabin decompression), a backup "in use" advisory or caution indicator should be illuminated. A backup quantity indicator should be provided to aid charging during ground service, pre-flight verification of charging, and in-flight estimation of remaining supply. In the F-16 LOX system, selection of backup (bailout supply) is by manual activation by the aircrew or automatic activation on ejection. In either case the crewmember is aware of backup oxygen supply activation and its limited quantity. The backup quantity is indicated by a cylinder mounted pressure gauge used only for charging. The AOS advisory indicators are analogous to those in conventional oxygen systems.

Summary of Recommended AOS Indicators

The complement of sensors and indicators suggested above is sufficient to inform the crew of the AOS status and to allow diagnosis of system faults. Some of the sensors and indicators may be eliminated or combined at the risk of loss of flexibility in detecting and analyzing system faults. The choice of the minimum set of sensors and indicators necessary to satisfy a particular aircraft installation is more a matter of opinion than a requirement. However, the preceding system failure review suggests the following sensors and indicators for any AOS installation.

a. Oxygen partial pressure sensor with OXY LOW warning indicator.

b. Product flow sensor and "blinker" indicator.

c. Cabin pressure sensor and cabin depressurization warning indicator.

d. Backup oxygen supply selection and warning indicator.

e. Backup oxygen supply quantity sensor and indicator.

AOS CONTROLS

The control scheme for an AOS is largely a matter of choosing the set of controls and designing the mode selection options necessary to give the aircrew the control flexibility they desire. The controls suggested here are conservative in the sense they form a set necessary to control the system and cope with all the MSOGS failures described above without undue risk. The combination of sensors, indicators, controls and aircrew procedures can be changed to suit specific installation constraints.

Operating Controls

The system ON/OFF selector is a multifunction control with at least three positions: OFF, MSOGS, and Backup. In the OFF position, the selector should de-energize the main electrical supply to the MSOGS concentrator. If necessary, an inlet air shut off valve could be closed when the selector is moved to the OFF position. It is desirable to positively seal the backup oxygen supply against leaks whenever the system is turned off. This feature may be incorporated in the AOS ON/OFF switch or perhaps a weight-on-wheels switch. Either signal could close a solenoid activated shutoff valve to seal the high pressure oxygen cylinder in the backup oxygen system.

In the MSOGS position, the AOS is placed in a mode designed to supply MSOGS gas to the regulator when the cabin pressure altitude is below the maximum during pressurized flight. For a tactical fighter with a 50,000 foot ceiling this is typically 23,000 feet or less. It highly desirable to deliver breathing gas of high oxygen content ($\%O_2 > 94\%$) from the backup supply immediately on decompression to prevent post decompression hypoxia (see Chapter 5). Therefore, the backup oxygen selector valve should be activated automatically on cabin decompression and the Backup "in use" indicator and the cabin pressure caution caption illuminated. Re-selection of MSOGS should be possible after automatic selection of backup. For flight in the decompressed state, a "lock out" of the automatic feature should be incorporated. A positive crew action should be required to return the breathing gas supply to the MSOGS when the cabin is decompressed. When MSOGS is selected, the Backup "in use" caption should be extinguished, but not the cabin pressure caution indicator. If cabin pressurization is restored, it should be possible to reset the automatic backup selection feature.

A similar scheme could employ the oxygen sensor warning signal to automatically select backup. The decision to include such a feature is really based on confidence in the reliability of the oxygen sensor rather than the desirability of automatic mode selection. If there are spurious false warnings generated by the oxygen sensor, the backup oxygen supply will be used unnecessarily. To avoid the effects of transient reductions, the system should not respond to transient reductions of the product gas pO_2 to as low as 130 mm Hg, provided that the duration of the reduction below 160 mm Hg does not exceed 10 seconds.

At a minimum, the manual Backup selector should be accessible and easy to activate. Selection of the Backup position should connect the regulator gas supply to the backup oxygen system and illuminate the Backup "in use" caution indicator. A positive action should be required to return the breathing gas source to MSOGS unless the backup oxygen supply is depleted. When the backup supply is exhausted, the breathing gas source should automatically switch to the MSOGS. The Backup "in use" indicator should be extinguished whenever the backup is not in use even though the control is in the Backup position.

Whenever the MSOGS is not supplying gas to the breathing regulator, a small "bleed" demand of about 5-10 L [STP] min^{-1} should be imposed on the concentrator so that the product gas reaches an equilibrium oxygen concentration corresponding to low demand. Any composition control system should be deactivated. So, if the MSOGS is re-selected, the initial product gas composition will be relatively oxygen rich. The "bleed" demand is usually extracted from the system selector valve, so that the product pipework between the concentrator outlet and the selector valve is flushed with oxygen rich product while the backup supply is selected. The oxygen sensor sampling point should be upstream of the selector valve so the sensor always measures product gas oxygen partial pressure.

In ejection seat aircraft, a seat mounted emergency oxygen supply should be activated automatically on ejection. Moreover, it should be possible to activate this supply manually. This supply may be physically part of the backup oxy-

gen supply if the latter is located on the ejection seat. There are definite advantages to carrying large bailout oxygen supplies, especially if a chemical defense respirator is to be ventilated after ejection.

Built-in-Test Controls

The suggested built-in-test (BIT) controls are designed to give the aircrew the ability to check the function of indicators and integrity of critical oxygen system components. Two tests are suggested: (a) a press-to-test (PTT) integrity check of the low pressure breathing circuit; and (b) a PTT of the oxygen sensor. The former is analogous to the PTT in a conventional oxygen system to verify the integrity of the low pressure portion of the breathing system. The latter test checks the oxygen sensor and warning (and central warning) indicator.

The integrity check is conventional. The regulator is employed to pressurize the low pressure oxygen circuit to several inches of water gauge pressure. While the oxygen mask is pressurized, the crewmember inhales, stops breathing and exhales while observing the flow indicator. The indicator should show "flow" during inhalation and "no flow" during exhalation and breath hold. An abnormal flow indication may indicate a system leak.

The oxygen sensor press-to-test should introduce an ambient air sample to the sensor cell. It should not be solely an electrical check. The test should activate the OXY LOW warning without activating the backup oxygen system.

CONCLUSIONS

Failure analysis provides a method for developing a rationale for choosing sensors, indicators and controls for an aircraft oxygen system. A review of potential failures in an MSOGS based advanced oxygen system shows that an oxygen partial pressure sensor is required for detection of critical failures of the MSOGS concentrator. Other AOS sensors and indicators are analogous to those in conventional oxygen systems, although their interpretation is somewhat different.

SUMMARY

The rationale for choosing sensors, indicators and controls for advanced oxygen systems is fundamentally the same as for conventional oxygen systems. The display should inform the aircrew of the status of the oxygen system and allow diagnosis and rectification of faults. Oxygen sensors play a central role in the safety and control of molecular sieve oxygen systems in advanced oxygen systems for military aircraft.

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Chapter 10

PRACTICAL ASPECTS OF THE DESIGN OF ADVANCED OXYGEN SYSTEMS

John B. Bomar, Jr.

INTRODUCTION

The motivation for building advanced onboard oxygen generation systems (OBOGS) for military aircraft is primarily to eliminate the disadvantages of the stored oxygen sources. Implicit in this concept is the assumption that the disadvantages of aircraft oxygen systems based on liquid oxygen (LOX) outweigh the disadvantages of OBOGS. The designer of an advanced oxygen system (AOS) quite naturally aims to employ OBOGS in an optimal way - exploiting the advantages of OBOGS while minimizing the adverse impact of OBOGS on the operational use and support of the aircraft. Many of the "practical" aspects of OBOGS described in this chapter deal with minimizing the adverse effects of an OBOGS installation on aircraft services and the life support system, including aircrew personal equipment. Moreover, as the term "practical" implies, most accurately, the practical aspects of OBOGS are lessons learned in practice. Undoubtedly, the future designers will continue to refine their MSOGS designs and add to the body of practical experience in the design and employment of Advanced Oxygen Systems.

APPLICABILITY OF OBOGS

The USAF at one time proposed a plan to define and develop a "Generic OBOGS" for fighter aircraft (28). This sparked a debate within the life support community on the question of the universal applicability of OBOGS within and across aircraft roles that deserves comment. Experience to date has shown, at a minimum, a unique interface design is required for each aircraft model fitted with an OBOGS. Indeed, for all USAF aircraft to date, the incorporation of OBOGS has been accomplished with contractor furnished equipment designed to contractor specifications. Thus, the debate on whether a "generic OBOGS" can be developed seems in reality to be a debate on the definition of the terms "generic" and "OBOGS." The once important question of whether or not *standardization* is desirable has become largely moot.

The argument for standardization is based on cost, including both development cost and maintenance cost. However, for new aircraft, standardization works against design flexibility, so it can be argued that OBOGS standardization should be minimized. For example, the oxygen concentrator need not be constrained to the shape or size of a LOX bay. The servicing frequency of a concentrator is much less than a LOX converter, so why not size the concentrator to fit an interior bay? This rationale may be extended to other parts of the AOS. Undoubtedly, each new aircraft design will require a unique AOS design to achieve the best performance of both the oxygen system and the aircraft. Thus, it would seem unwise to standardize on OBOGS for future aircraft. To do so is to give up flexibility and the opportunity to advance the design of the life support system at the same rate as aircraft design advances.

On the other hand, standardization is attractive for retrofit of AOSs to aircraft originally designed to accommodate a LOX converter. The US Navy has begun an extensive program to retrofit OBOGS into their carrier based aircraft fleet (2,18), and has adopted a workable solution to standardization by specifying a common two-man molecular sieve oxygen concentrator, oxygen monitor and regulator (21).

Applicability of molecular sieve oxygen generation (MSOG) systems to a particular aircraft type is contingent to some degree on the aircraft's operational role. Conceivably, an MSOGS could be designed for any aircraft type, though the size and configuration of the system will be strongly influenced by aircraft crew complement, size and performance. The reduced logistics tail of MSOG systems makes them ideal for dispersed based aircraft such as strategic bombers or forward based tactical fighters and, especially, ship based aircraft. The jet VSTOL fighter, such as the RAF Harrier GR Mk5 or the US Navy AV-8A/B Harrier, heads the list. This is undoubtedly the reason the Harrier was first operational aircraft equipped with an MSOGS (14).

At the other end of the spectrum, are primary jet trainers. These aircraft typically have low power turbojet or turboprop propulsion with concomitant low engine bleed air pressures. They operate over short ranges from fixed, generally safe, rear echelon bases where established LOX and GOX handling facilities are available. These aircraft are less suited for an MSOGS installation because: (a) the advantage in eliminating the LOX or GOX servicing is small; and (b) a suitable compressed air source for MSOGS is difficult to provide. Nonetheless, the Japanese have developed an onboard oxygen generating system for their new intermediate jet trainer, the XT-4 (30). Similarly, rotary wing and unpressurized aircraft are relatively less well suited for MSOGS, though a system for rotary wing application has been proposed (7).

It is doubtful whether MSOGS will become the universal oxygen system technology for all military aircraft. However, OBOGS, in general, and MSOGS, in particular, offer unique advantages over conventional oxygen systems, so it is reasonable to say MSOGS has found a permanent place in military aviation as a viable technology for aircraft breathing systems. The rest of this chapter is devoted to describing some of the practical design requirements affecting the applicability of MSOGS to any aircraft installation. Careful consideration of the unique capabilities and requirements of MSOGS will aid in defining the suitability of MSOGS for a particular application.

MSOGS SIZING

In contrast to stored supply oxygen systems, the size of an MSOG system is dependent on flow capacity and product oxygen composition rather than worst case mission duration. Once the concentrator design is worked out, the size and capacity need change only to accommodate additional crew stations or a radically different oxygen composition requirement - both affect the required flow vs composition criteria. Scaling typically means adding more beds or increasing bed capacity, although it may be possible to get increased performance by simply increasing the inlet pressure. A design optimized for one application will typically require scaling if the number of crew stations is increased. It is prudent to build in growth capacity if crew station increases are anticipated, such as in two seat versions of single-seat fighter aircraft.

The scaling of MSOGS oxygen concentrators to accommodate changes in product oxygen composition or flow capacity requirements has remained an empirical science. It was indeed fortunate that the size of a fighter aircraft LOX bay accommodated a molecular sieve oxygen concentrator large enough to meet the needs of two crewmembers. Several two and three bed designs have been shown to satisfy the flow capacity and oxygen enrichment requirements for the single- and dual-seat tactical fighter under practically all operational and environmental conditions applicable to conventional oxygen systems.

As the number of crew stations increases to three and beyond, a tactical MSOGS can no longer supply the flow or air enrichment needed for the entire performance envelope. For a particular concentrator design, if the molecular sieve formulation is fixed, a "worst case" controlling condition will exist which will drive the scaling of the concentrator. This point is the combination of bed capacity, operating and environmental conditions where the product composition or flow just fails to meet the physiological criteria. To increase the concentrator's capacity, the designer can either increase the size of the beds or increase the number of beds, or both. Because the beds act as pressure vessels, bed size increases will mean increases in wall thickness resulting in extra concentrator weight. This can be traded off with weight increases due to adding more beds, pipework and support structure. Ideally, some designed-in overcapacity should be provided as a safety margin.

In general, performance scaling factors for oxygen concentrator size differ with bed design and configuration (20). Moreover, geometrical scaling will usually require cycle timing adjustment to optimize the efficiency of the scaled concentrator under the given conditions. Unfortunately, little help is available to guide the designer in how to scale an MSOGS concentrator. The USAF has sponsored a considerable effort to develop a mathematical model of the AV-8A oxygen concentrator (1)(See also Chapter 6). For that system, it appears changes in performance predicted by changes in geometric scale alone are quite accurate as long as the assumptions of the mathematical model are not violated. However, alteration in gas flux profiles within the beds or loss of flow symmetry may require model alterations to restore accuracy of predictions. Nevertheless, mathematical modeling of a particular design may be employed for scaling as long as the model assumptions are not violated in the scaling process.

Litton Instruments and Life Support Division has described an empirical scaling method for sizing multi-crew MSOGS systems (20). They advocated optimization based on one of two criteria: (a) input/output - where the air consumption is minimized for a given product flow/composition requirement; and (b) a productivity criterion - where the efficiency of the concentrator is optimized to achieve the highest product flow per unit volume of molecular sieve under fixed conditions of product composition, temperature, altitude and inlet pressure. The optimization procedure is carried out by measuring the criteria under a sufficient range of concentrator sizes to span the optimization space. Optimum performance is interpolated and the size nearest the optimum, but exceeding the required capacity is identified. This procedure should work for scaling the size of individual beds or simply increasing the number of beds. Obviously, a more practical (and less expensive) method for estimating the scale factors and predicting the performance of scaled MSOG systems would be welcomed by industry and government alike.

Regardless of the method used to scale the MSOGS, the performance of the revised design must be verified by laboratory assessment under realistic simulated conditions. Particular attention should be directed to defining the dynamic behavior of the system in response to dynamic demand and changing environmental conditions.

MSOGS INSTALLATION REQUIREMENTS

Undoubtedly, each AOS installation will be unique — with unique advantages and tradeoffs. There are, however, several requirements common to most MSOGS installations that can be discussed in general terms. Usually, the overriding consideration is finding a suitable source of compressed air for the MSOGS concentrator. For aircraft installations, bleed air is the obvious choice as the source of air for the MSOGS. The quantity of bleed air required for the MSOGS is rarely significant in relation to the total supplied for the environmental control system and cooling of avionics. However, within the bleed air distribution system, the highest pressure bleed air is also the hottest. It is axiomatic that relatively less cool bleed air is available at high enough pressures to supply the MSOGS. Further, the "budget" for conditioned bleed air is always "tight" because of the large quantities required for cooling avionics. Thus, even though the MSOGS bleed air allocation is relatively small, if taken from a marginally adequate system (as in a retrofit) there may be an undesirable effect on other aircraft systems. In some aircraft, the pressure and quantity of bleed air is simply inadequate for an MSOGS supply. In such cases, the only recourse is to employ compressors to boost the pressure of the bleed air or even to supply all the MSOGS air. The inclusion of an inlet compressor in the MSOGS introduces another component into the system resulting in reduced reliability. So far, MSOGS has not been employed in aircraft with very low bleed air pressure schedules.

Concentrator Location

For new aircraft designs, MSOGS offers a great deal of flexibility compared to conventional oxygen systems. The concentrator may be placed close to the cockpit to shorten product line pipework to cut downstream pressure losses. In fact, the concentrator may be put in the pressure cabin, as

long as the exhaust is vented overboard or to an unpressurized area of the aircraft. Routine servicing of the concentrator is not required, so it may be installed in an interior bay, as long as it can be removed for replacement in the event of a failure. If, however, it is desired to design the oxygen system to accept either an MSOG concentrator or a LOX converter, then a LOX bay installation may be the most desirable. If possible, the orientation of the concentrator should place the long axis of the molecular sieve beds (usually the major axis of the gas flow path within the beds) in line with the $+G_z$ acceleration axis for the aircraft. If the beds are oriented out of the vertical, particular care should be taken in packing, immobilizing, and retaining the molecular sieve to prevent channeling of gas flow within the beds.

In a retrofit installation, the concentrator is almost always relegated to the bay vacated by the LOX converter. This is obviously the most convenient location, if a suitable source of bleed air can be routed to the LOX bay. Another key consideration in retrofit is the length and bore of the pipework extending from the LOX bay to the cockpit. Pressure losses in the existing oxygen system pipework may be unacceptable, if the LOX bay is located more than a few feet from the cockpit. In such cases, the existing product delivery piping may have to be replaced with a larger bore and/or a plenum may be required near the breathing regulator to prevent regulator starvation. The tradeoff between pressure loss and volume capacity of the product delivery pipework must be examined carefully. Too much volume between the regulator and the concentrator or backup oxygen supply (BOS) can cause excessive delays in the delivery of high purity product or BOS gas in the event of loss of cabin pressurization. Additionally, the pressure fluctuations at the concentrator outlet may interact unfavorably with the demand regulator if the impedance of the supply pipework is not matched to the regulator.

Compressed Air Supply

The average mass air consumption of an MSOGS will depend primarily on the difference in inlet and exhaust pressures, the size of the unit and the timing of the charging and purging cycles. For a typical concentrator air consumption is not a strong function of product demand flow. Air consumption typically rises only about 35 per cent as demand flow rises from no flow to full flow. Cramer (10) has suggested a rough rule of thumb for estimating air consumption at a particular operating point. He suggested average air consumption will be approximately 30 times the oxygen production on a mass-mass basis. Thus, for a single person breathing 15 L (STP) per minute of a gas containing 50 percent oxygen, the concentrator air consumption would be approximately 0.7 lb (0.3 kg) min^{-1}. Air consumption of 1-1.5 lb (0.5-0.7 kg) min^{-1} is typical of concentrators designed to supply two crewmembers. Note that this implies a typical air separation efficiency of about 17 per cent compared to perfect separation that would require roughly 5 lb (2.3 kg) of air for every 1 lb (0.5 kg) of oxygen produced. For larger units air consumption is higher. For example, the bleed air consumption of the MSOG system on the USAF B-1B is about 4 -4.5 lb (1.8-2.1 kg) min^{-1} while supplying six crew stations under simulated flight conditions (8).

The product gas flow capacity and air separation efficiency of an MSOGS concentrator are dependent on the concentrator inlet pressure. If the inlet pressure falls below a certain limit, the oxygen concentration of the product at a given product gas flow rate will decrease. Reduction of the inlet pressure also reduces the concentrator outlet pressure, and, thus, the maximum (peak) flow capacity through the concentrator. As discussed in Chapter 6, most molecular sieve oxygen concentrators are designed to an upper pressure limit of 50-70 lbf in^{-2} gauge (345-483 kPag) to limit the consumption of bleed air.

The air enrichment performance of an MSOGS concentrator becomes significantly impaired at pressures below about 15 lbf in^{-2} gauge (103 kPag)(referred to the exhaust pressure) (5,15, 22,27). The worst case for oxygen concentration in flight will usually be found under idle descent from high altitude, where the reduced engine power setting leads to lowered bleed air pressure. The worst case for flow delivery will usually occur during ground idle conditions where the crew may notice increased breathing resistance on inspiration. An outlet plenum may be warranted to provide enough capacitance upstream of the breathing regulator to cope with high peak demands during periods of low concentrator inlet pressure.

Because of the cyclical nature of the charging and purging of the molecular sieve beds within a concentrator, the air flow into the device is cyclical. Peak mass flows into an MSOGS concentrator (supplied from a large reservoir) are typically 3 to 5 times average mass flows (27). The dynamic nature of the flow demand should be considered when sizing the inlet pipework. Excessive impedance in the air supply pipework can lower average inlet pressures, and thereby impair oxygen enrichment efficiency, effective delivery pressure and peak flow capacity of the system. The bleed air pressure schedule at the proposed pressure tapping should be examined for dynamic flow and pressure characteristics under the full range of aircraft altitude and power setting combinations. Computer models of the aircraft's bleed air distribution system are useful adjuncts to actual measurements in determining the best location for a bleed air source tapping.

Requirements for thermal conditioning of the inlet airstream are driven by the sensitivity of the air separation process to extremes in temperature. For best operation the steady state inlet air temperature should remain within the range of 0-60°C. Miller et al (22) and others (15,20,27) have shown the efficiency of air separation to decline significantly at temperatures above 70°C or below - 20 °C. A lower limit of 0°C is suggested to prevent freezing of water and the effects of ice within the inlet filter and pipework of the concentrator. Some designers have incorporated inlet air or bed heaters to keep the bed temperatures well above freezing. For example, the AV-8 concentrator employs a thermostatically controlled heater to heat the inlet air to 40-50°C, whenever the inlet air temperature is below 40°C. The U. S. Navy has reported results of cold soak testing on the AV-8A concentrator (27). After a four hour cold soak at -54°C, the unit delivered at least 55 percent oxygen gas at 13.1 L [NTP]min^{-1} after 25 minutes, even when -26°C air was supplied to the inlet. Under simulated rapid ascent, 55 percent oxygen was reached at 12,000 feet. Since engine bleed air is usually supplied at a temperature above freezing, cold temperatures are rarely, if ever, a problem in flight.

In practice, over an hour is required to stabilize the tempera-

ture of a two or three bed concentrator after a step change in inlet air temperature. It is doubtful that a concentrator in an aircraft ever reaches thermal stability. Because the thermal inertia of the concentrator ensures bed temperatures change very slowly, inlet air temperatures in excess of 100°C can be tolerated for a few minutes with little effect on concentrator performance. If, however, bleed air is supplied continuously at temperatures above 60°C, the concentrator performance will be adversely affected. In such cases, a dedicated bleed air heat exchanger may be required to condition the MSOGS supply air.

The effects of inlet air contaminants on a MSOG concentrator are discussed fully in Chapter 11. Suffice it to say, in practice, MSOGS concentrators are very insensitive to the presence of inlet air contaminants, as long as the pressure charge and purge cycle is functioning properly. Inlet air filters separate solid and liquid contaminants from the inlet air stream and the purge cycle flushes the majority of gaseous contaminants into the exhaust.

Electrical Power

The mechanical functions of an MSOGS concentrator can be powered by the pressure of the inlet air supply (See the discussion of the USAF AOS in Chapter 8.) The use of electrical power for switching or driving valves is more a matter of convenience than an absolute requirement. It is certainly easier to implement the logical functions of MSOGS control in electronic rather than fluidic control circuits. Moreover, the power requirement for the operation of a typical concentrator is only a few watts. Indeed, if heaters are employed, the heater power requirement will exceed that of the pressure cycle switching and logic circuit by many-fold.

Power can be supplied from a variety of aircraft sources. It is preferable that the control logic and valve drive circuits (but not heater circuits) are supplied from an essential power bus, so that power is supplied to the oxygen concentrator as long as power is available. In concentrator designs susceptible to degradation by continuous flow, an inlet air valve should be provided to automatically shut off the air supply whenever power to the concentrator is lost.

Environmental Considerations

All parts of an MSOGS for use in NATO must meet the requirements of NATO STANAGs 2831 (24) and 3518AE (25), which give the climatic conditions and environmental test methods for aircraft and ground equipment. Components for use in USAF Aircraft must meet the requirements of U.S. MIL-STD- 810, entitled, "Environmental Test Methods and Engineering Guidelines" (23). The UK Environmental Standard is British Standard 3G.100, "General Requirements for Equipment for Use on Aircraft" (6). These documents offer guidance on testing aircraft components in extremes of temperature, pressure, vibration, acoustic noise and shock, as well as simulated climatic extremes. For MSOGS components, some special considerations are appropriate in guiding the design tailored environmental tests. The final environmental compatibility will be proven in development flight testing, where the actual environmental conditions will exist (simultaneously). Every effort should be made to test the assembled MSOGS in controlled environments simulating as much of the expected flight envelope as possible.

Temperature: For the MSOGS concentrator, the most important consideration is the temperature of the molecular sieve beds. The bed temperature will be a function of the temperature of the supply air, the air surrounding the concentrator, the temperature of the supporting structure(s) and the radiant heat exchange with the surroundings. Besides the temperature requirements for inlet air, the thermal environment in the concentrator bay should be such that the bed temperature stays within the 0-60°C range suggested above. If temperature sensitive oxygen sensors are installed within the concentrator itself or within the concentrator bay, a more narrow range of operating temperatures may be appropriate.

Barometric Pressure: The MSOGS must work within the full range of ambient pressures found in the flight envelope. Additionally, the part of the MSOGS located within a pressurized compartment must be capable of withstanding the effects of rapid decompression.

Vibration, Shock, and Acoustic Noise: In addition to standard requirements, particular attention should be paid to vibration or shock induced powdering of the clay binder matrix in molecular sieve formulations. The concentrator should be operated during vibration testing to simulate realistic conditions. The combination of pressure swing and mechanical vibration may cause dust generation when neither stress would produce it alone. The concept of bed immobilization is discussed in Chapter 6.

Electromagnetic Susceptibility or Interference: All MSOGS circuitry should be tested to the same electromagnetic compatibility and nuclear hardness requirements as other aircraft circuits.

STANDBY, BACKUP, AND BAILOUT SYSTEMS

A unique disadvantage of OBOGS is the need to supply breathing gas from a source other than the oxygen generator whenever the engine bleed air is not available. There are several practical approaches to solving this problem, all of which involve compromise to one degree or another. Others are under development with the aim of making MSOGS systems completely "self-contained," thus eliminating their reliance on outside sources of breathing gas.

The same definitions used in Chapter 9 for "standby" and "backup" will be adopted for this chapter. The term "standby" will mean a non-emergency situation where the aircraft engines are not running and the term "backup mode" will refer to an emergency change of the breathing gas source to a backup oxygen supply (usually gaseous oxygen). The "bailout" oxygen supply is the emergency supply used after ejection at altitude.

Standby Breathing System

In NATO, there is a requirement for dispersed aircraft to adopt a combat alert posture in the presence of an airborne chemical or biological threat. This scenario has focused attention on the need for a source of clean breathing gas prior to engine start. The man-mounted nuclear, biological and chemical (NBC) filter, which is part of the aircrew NBC ensemble, will be used to filter the breathing gas to meet this requirement in current systems. For aircraft equipped with conventional oxygen systems, any cabin air introduced into

the breathing system will be routed through an NBC filter. In some NBC protective systems, the entire breathing gas supply flows through the man-mounted NBC filter to the aircrew NBC respirator.

The requirement for clean breathing gas exists in the non-NBC situation as well, but it has been assumed the crew could breathe cabin air. In almost every conceivable training scenario (and most operational scenarios) for combat aircraft, crew members are fully strapped in to the aircraft seat before engine start. It is not uncommon for tactical aircrews to wait 15 to 20 minutes while other aircraft start engines, taxi and takeoff. With conventional oxygen systems, aircrew normally don their oxygen mask for communication, and sometimes breathe 100% oxygen for protection against noxious exhaust fumes from other aircraft. Whether true or not, operational crews believe exhaust fumes and gases to be harmful if breathed. Even if jet engine exhaust is not frankly toxic, most would agree it has an unpleasant odor. So, it seems desirable to have a source of breathing gas other than cabin air for optional use before engine start.

In an MSOGS, at least as currently implemented in operational aircraft, the only breathing gas available before engine start besides cabin air is the emergency backup supply. The routine use of emergency systems is considered poor practice from the flight safety point of view. Emergency supplies are sized on worst case emergency scenarios. If the backup is partially depleted by routine preflight use, the quantity of backup oxygen may not be adequate for an actual in-flight emergency. If the backup supply must be serviced regularly due to routine use, the logistics advantage of MSOGS is compromised. Moreover, routine use of valves designed to be hermetic seals at 1800 lbf in^{-2} g (12,400 kPag), will eventually lead to wear of the seals and leakage of the backup gas. The conclusion is clear - high pressure emergency gas stores should not be used routinely for preflight breathing. A "weight-on-wheels" backup shut off switch may be used to prevent use of the backup system on the ground, as well as to prevent leakage from the backup system.

Thus, with existing MSOGS technology, it is apparent that the crew must breathe cabin air before engine start. The system implemented in the Tactical Life Support System (TLSS) goes the next step (See Chapter 8). The TLSS MSOGS has a cabin air bypass valve incorporated in the regulator. At cabin altitudes below 9,000 feet, the cabin air bypass opens whenever there is no pressure at the regulator inlet. When the valve is open, cabin air passes to the regulator outlet and then to the oronasal mask when the crewman inspires. In the NBC mode, the inspired gas passes through a man-mounted filter before it enters the respirator. This system allows the crewmember to keep his oxygen mask on before engine start and after a loss of regulator supply pressure, but it does not offer any protection against exhaust fumes in the non-NBC mode.

One standby supply alternative would be to supply compressed air to the MSOGS from an external ground cart air compressor. This procedure might work for normal training, but it makes the MSOGS dependent on ground equipment, which imposes an unacceptable logistics burden on the system in combat. An electrically driven airframe mounted compressor could supply the MSOGS inlet to make the MSOGS independent of engine bleed air. There is probably not enough aircraft electrical power to supply such a compressor unless the engines are running, so the system would be dependent on external power. This is a marginal improvement over a ground compressor, but still unacceptable logistically. Newer tactical aircraft may incorporate auxiliary power units (APUs) which can be used to supply both electrical power and bleed air to the MSOGS concentrator, and thus provide product breathing gas to the aircrew during ground alert.

One solution to the standby breathing gas supply requirement in retrofit installations is to generate, accumulate and store the supply onboard the aircraft for use before the next flight. The USAF has begun development of a hybrid oxygen system to meet such a requirement, using cryogenic liquefaction for storage of the gaseous product from MSOGS (19).

Backup Oxygen System

The backup oxygen supply is intended to provide an alternate supply of breathing gas to the crew in the event of loss of the air supply to the MSOGS concentrator (for example, engine flame out) or immediately following a loss of cabin pressurization. The quantity of backup oxygen required is determined by estimating the breathing requirements for the worst case backup use scenarios. Typically, the descent from high altitude after a loss of engine power is the worst case for backup use. Additional gas must be added, if the backup system is employed to ventilate an NBC respirator in the event engine failure is accompanied by loss of electrical power. Such a scenario will yield a backup requirement in excess of 200 L (NTP) of oxygen per crewmember, which will provide ample backup (with a margin of safety) for the other situations.

The backup supply should be designed and located so that ground maintenance crews can easily and quickly replenish or top up the supply without special equipment. As described in Chapter 9, the control of the backup should be automatic with manual override. The pilot should be able to manually select the backup system whenever desired, regardless of the mode selection of the MSOG system's automatic control system. At a minimum, backup oxygen should be automatically selected on decompression of the cabin to altitudes above 22,000-25,000 feet (MSL). Automatic selection may be provided in response to other hazardous conditions such as low oxygen partial pressure of the breathing gas, low MSOGS system pressure, high concentrator temperature, etc. The crew should be able to manually override backup selection in any mode and the system should automatically override backup selection when the backup oxygen supply is depleted.

The contents of the backup oxygen system should be indicated to both the air and ground crews with a clear, simple quantity indicator. The labeling of the contents gauge should be considered carefully. It is more important that the crew be able to quickly check the quantity, than read the quantity precisely. Major divisions such as thirds, quarters or half full contents should be emphasized. Color coding to indicate the remaining quantity is suggested. A system combining the color green with the "FULL" indication, yellow with one-third or one-quarter supply and red with "EMPTY" gives the crew the necessary information quickly without over complicating the markings. If the emergency bailout

supply is combined with the backup, the "EMPTY" indication should be marked at the volume corresponding to the full emergency bailout supply volume (ca. 70 L [NTP]). The width of the markings (color bands) should be sufficient to prevent false indication under temperature extremes. Further, maintenance instructions should give appropriate filling instructions for different temperature ranges to prevent under- and over-filling. For example, a backup system filled in the a realistic hot condition should read FULL in a realistic cold condition. Nor should it be necessary to bleed gas from a system filled in cold conditions and subsequently flown into hot conditions.

High Pressure Gaseous Oxygen: The most straightforward implementation of a backup supply is to store gaseous oxygen at high pressure (1800 lbf in^{-2} gauge)(12,400 kPag). The physical size and weight of the pressure vessel and the mounting site together with the available space set the upper limit on the quantity of stored gas. In an ejection seat-mounted installation, the practical upper limit in backup quantity is roughly 200 liters (NTP) per seat. This is in contrast to the B-1B MSOGS which contains a backup sphere holding 2200 L (NTP) of oxygen mounted adjacent to the concentrator in the equipment bay aft of the crew compartment. In fighter aircraft, larger supplies can be accommodated by airframe mounting, however, the advantage of combining the backup and emergency bailout supplies is lost.

The biggest disadvantage in the use of high pressure gaseous oxygen for MSOGS backup is the difficulty in preventing leakage from the system. If the system were "onetime use," it could be sealed with a leak free rupture disk or similar facility. However, the requirement to cycle the system on and off means that valves must be employed for sealing and flow regulation. At 1800 lbf in^{-2} gauge (12,400 kPag), some leakage can be expected from the best of valves. The specification for leakage should be carefully considered in view of the technology available and the servicing requirement imposed by system leakage. Specifications should be written to limit both internal (across the valve) and external (to the external atmosphere) leakage. The external leakage specification should apply both when the valve is open and when it is closed. A backup system ON/OFF valve may be included to positively lock off the backup supply at the source. For example, a weight-on-wheels switch may be used to control a solenoid operated system ON/OFF valve to prevent leakage before takeoff and after landing, but it should not prevent the crew from manually activating the system, if necessary.

The pressure of the backup oxygen system must be reduced upstream of the demand regulator by a pressure reducing valve (pressure regulator) and the flow controlled by the pressure reducer and the valve used to select the backup. Two configurations of the selector and reducing valves are possible: (a) selector valve followed by the reducing valve; or (b) the reducing valve followed by the selector valve. Arrangement "a" has the advantage of lower system leakage since the selector valve is typically a fully open or fully closed valve, designed for low leakage. Further, arrangement "a" usually can be configured to expose less of the backup pipework to the high pressure, thus reducing the external leakage rate. The tradeoffs for "a" are: (i) higher operating forces on manually opening and closing the selector valve; (ii) a tighter total leakage specification for the selector valve; and (iii) less design flexibility for the selector valve (a consequence of "ii"). Arrangement "b" has as its main advantage, greater flexibility in the design of the selector valve and lower selector valve operating forces. The disadvantages of arrangement "b" include: (i) increased total leakage and (ii) tighter leakage specification for the reducer valve. Note that all reducing valves must pass a finite flow to function. Unless the selector valve relieves the reducer control flow, the parts of the backup system between the bottle outlet and the pressure reducer will be exposed to high pressure until the onset of full flow. Thus, if the selector valve is designed to be very leak tight, then either: (i) a relief valve must be installed in the pipework between the reducing and the selector valves; or (ii) the pipework upstream of the selector must be designed to withstand high pressure, thus negating the main advantage of arrangement "b". So, in practice, arrangement "b" must leak a small amount of backup gas to gain its design advantages. A system ON/OFF valve installed upstream of the reducer may be employed to minimize leakage when the aircraft is not in use. The disadvantage of a system ON/OFF valve is it must be reliably controlled - this may necessitate a ground crew action, which is undesirable. If the system is inadvertently left OFF during flight, the results could be disastrous.

Medium Pressure Gaseous Oxygen: If more space is available, backup may be stored at medium pressure (ca. 300-450 lbf in^{-2} g (2,070-3,100 kPag)). This has the advantage of generally reduced external leakage rates and simpler flow control and pressure regulation. The storage capacity of low or medium pressure cylinders can be enhanced by filling with molecular sieve. At 400 lbf in^{-2} gauge (2760 kPag), the storage capacity of a given volume can be increased by a factor of about three, by filling the volume with 5A zeolite molecular sieve formulation. There is no advantage in using this technique with high pressure oxygen. The break-even pressure is approximately 1470 lbf in^{-2} abs. (10,100 kPaa) (16).

Chemical Oxygen: This technology is based on generation of high purity oxygen by chemical reactions. The most common method employed is the decomposition of sodium or potassium chlorate, commonly known as "chlorate candles." (See Chapter 3.) Chlorate candles are composed of almost pure sodium chlorate with additives to sustain and control the rate of decomposition. The gaseous decomposition product is nearly pure oxygen (>99.5%) with several trace impurities including: water vapor, carbon dioxide, carbon monoxide and chlorine. Water vapor dominates the impurities with the rest being present in safe concentrations (17). The candles are packaged in insulated metal cylinders and are ignited by electrical means or percussion caps. Once ignited a single candle will decompose completely — there is no practical means to stop the decomposition. The difficulty in employing chlorate candles is in regulating the flow of gas and the system pressure and temperature. Several candles are usually connected to a manifold accumulator system. The candles can be ignited singly or multiply in sequence or parallel as needed to keep the system pressure above some specified minimum. A relief valve is included to limit the maximum pressure. Two concerns have been raised regarding the use of chemical oxygen as an MSOGS backup source: (a) the rate at which gas can be delivered on initial ignition, and (b) the high temperature generated by decomposing chlorate compounds. The first concern arises in systems containing accumulators. It takes

tens of seconds to generate enough gas to raise the pressure of the system sufficiently to drive a demand regulator. If the accumulator size is reduced, gas will be wasted through venting after the accumulator has been pressurized. So, the tradeoff is sizing the accumulator(s) to store generated oxygen versus the pressure build-up rate. The second problem can be solved by conducting the heat away from the generator. Obviously, heat exchange machinery and insulation add weight to the system and extra space may be required to prevent thermal damage to adjacent equipment. The U. S. Navy is developing a chemical oxygen emergency supply system to replace the high pressure gaseous oxygen systems in its aircraft (3).

Onboard Generation: One attractive method of providing a backup oxygen supply is to generate and accumulate breathing gas with high oxygen concentration (ca. 94% or greater) on board the aircraft. Such a system has been developed by Litton for the McDonnell-Douglas F-15E fighter aircraft (29). The details of the system are described in Chapter 8. The concentrator product is stored in a molecular sieve filled plenum for use both as backup and standby breathing gas. The concentrator performance is monitored so that only gas with high oxygen concentration is stored. The quantity of gas stored is approximately 260 L (NTP) of greater than 93 percent oxygen.

Substitution of >90% oxygen gas for 99.5% aviator's breathing oxygen (ABO) raises the question of whether such gas will be physiologically equivalent. On the surface, all that is necessary to maintain adequate alveolar oxygen partial pressure is to deliver the lower concentration gas at a proportionally higher breathing pressure. The known physiological limits to positive breathing pressure will limit the maximum ceiling for the use of gas with lower oxygen content than aviator's breathing oxygen, but this may be of little practical significance. Further questions remain on (a) the effect of delivering lower concentration oxygen gas after a rapid decompression, and (b) the minimum pre-decompression inspired oxygen concentration to prevent severe transient hypoxia after a rapid decompression. The USAF (Armstrong Laboratory) has conducted a series of experiments to investigate the use of reduced oxygen content gas as a substitute for Aviators' Breathing Oxygen (ABO)(4). ABO is nominally at least 99.5% oxygen. USAF investigators substituted mixtures of 93%, 90%, and 85% oxygen and nitrogen for ABO in a series of rapid decompression experiments to 50,000 feet. The test subjects wore standard USAF aircrew breathing equipment and breathed from a standard USAF diluter-demand regulator. The researchers concluded that there were no important physiological differences between ABO and 93% oxygen, but that both were only marginally acceptable for use at 50,000 feet. It was concluded that further reductions in oxygen concentration below 93% were unacceptable for use above 47,000 feet (See Chapter 5).

It might be said that breathing less than pure oxygen at high altitude might impose additional decompression sickness (bends) risk on aircrew after rapid decompression. This is unlikely to be the case. The risk of bends is primarily determined by the concentration of nitrogen in the gas breathed before the decompression, not after. Parenthetically, there is a decompression sickness question remaining on the use of MSOGS product gas for aircraft requiring pressure suits, but this is not related to the AOS per se.

Emergency Bailout System

The major requirements for the emergency bailout oxygen supply are that it be ejection seat-mounted and that it supply enough gas to meet the requirements of the worst case bailout scenario (See Chapter 5). The supply should be automatically activated on ejection, but it should also be easy to manually activate in any emergency. The backup and emergency bailout supplies may be combined into a single seat-mounted supply. This has the advantage of providing a larger bailout supply and saving space on the airframe. If the oxygen regulator is seat-mounted there may be maintenance advantages in having the backup supply seat mounted. Most bailout systems in use today are supplied by high pressure oxygen cylinders, although the U. S. Navy is developing a chemical oxygen emergency system (3). Emergency breathing gas may be supplied through the demand regulator if the regulator is mounted on the man or ejection seat or, if not, it may be introduced directly into the low pressure breathing hose after pressure reduction. If the MSOGS regulator is a non-dilution regulator, the quantity of emergency bailout oxygen required will be increased over systems that dilute the breathing gas at low altitude.

PRODUCT OXYGEN COMPOSITION SENSING AND CONTROL

Several generic techniques are available for control of product oxygen composition. The specific implementation of a technique will vary with the concentrator design, but the methods are generally applicable to any design. The principle of pressure swing adsorption on zeolite has been described in Chapter 6. Any of the factors which affect the product composition may be used to control the oxygen enrichment. Two techniques that have been employed successfully are timing of the charge and purge cycle, and artificially increasing the product mass flow by adding a controlled bleed in parallel with aircrew demand. Other possibilities are: (a) altering the purge flow; (b) regulation of the pressure swing by inlet or exhaust flow and pressure control; or (c) diluting high purity product with air.

As with other control systems, composition control schemes may be classified as "open loop" or "closed loop," depending on whether the controlled variable is measured and used in the control scheme. The term "loop" is short for "feedback loop." If the output level (or the dynamic behavior) of the controlled variable is *not* employed in control then the system is classified as "open loop." If information about the level or its dynamics *is* used, the system is classified as "closed loop."

As it relates to control of MSOGS product gas composition, an open loop control system operates on assumptions about the concentrator's performance in response to the input operating conditions. In such a system, there is no real attempt to control the concentrator efficiency other than limit the operating conditions to those considered safe for the particular application. The concentrator efficiency (and product oxygen composition) is determined solely by the condition of the molecular sieve, the concentrator design and the environmental and operating conditions. Because the open loop system is not under control, it is prudent to include a product oxygen composition monitor as a warning device to warn of concentrator failure.

A third category, pseudo-closed loop control has been employed in MSOGS product composition control. Pseudo-closed loop uses knowledge about the MSOGS concentrator performance as a function of its operating variables rather than product oxygen composition per se. If performance is known as a function of operating conditions, oxygen concentration may be inferred from other variables. Manipulation of operating variables is then used to control the concentrator efficiency and thus the product composition. This control method is by no means foolproof — deactivation of the molecular sieve may lead to lowered product oxygen concentration without a detectable change in other variables. If the MSOG system has an oxygen composition monitor to detect a failed condition, the pseudo-closed loop control system may be employed effectively. The pseudo closed loop control system should incorporate the signal from the warning system to place the concentrator in as high an efficiency state as possible.

In general, closed loop control systems are inherently more exact in controlling oxygen composition than open loop systems. However, closed loop systems by definition require sensing of the product oxygen composition that may be a liability in some applications. Moreover, because the response of MSOGS concentrators to changes commanded by the control system is typically slow, there is inherent delay in the feedback loop that may lead to poor control system stability. The choice of control variable and sensor response may significantly affect the control of product oxygen composition. It may be better to control the rate of change in oxygen composition rather than the level itself if the oxygen monitor has a long response time constant. Conversely, it may be desirable to intentionally decrease the response of a rapidly responding sensor to damp responses to transient excursions in oxygen concentration.

The importance of oxygen sensors to AOS has given rise to considerable interest in oxygen partial pressure sensors for military aircraft (9,11,12,13,26,31). High sensor reliability is essential if sensor failure is indistinguishable from system failure. In systems containing closed loop control of the product composition, the best approach to system reliability is to include separate warning and composition control sensors. The ideal requirements for an AOS oxygen sensor are listed below.

a. Small and light weight.
b. Insensitive to changes in total pressure and temperature.
c. Long, reliable operational life and extended shelf life.
d. Low power consumption.
e. Rapid response/recovery and rapid warm up from "cold start."
f. Insensitive to orientation, vibration and acceleration.
g. Present oxygen concentration in nearly real time.
h. Accurate to within ± 5 percent, including drift.

Current oxygen sensor technology can be classified into five broad areas: (a) acousto-mechanical (fluidic, acoustic frequency and phase shift), (b) electrochemical (amperometry, voltametry, polarography, coulometry), (c) spectrometry (mass spectrometry, ultraviolet spectrometry), (d) solid-state (heavy metal-oxide bulk phase and thin-film semiconductors), and (e) paramagnetism. Polarographic sensors have been incorporated in MSOGS systems (15, 27). Both the AV-8A and F-16 Demonstration OBOGS employed a monitor based on a commercially available polarographic sensor. The polarographic sensors need both altitude and temperature compensation. Limited shelf life and environmental tolerance are further concerns. Normalair-Garrett Limited (NGL) has described a fluidic sensor designed specifically for oxygen concentration measurement in aircrew breathing gas (11). NGL has incorporated the sensor into warning and composition control device for aircraft oxygen systems. It is employed in the MSOGS of the Harrier GR5/7 (See Chapter 8). The fluidic sensor also requires altitude and temperature compensation. While the fluidic sensor has no shelf life limitation, it does require a clean reference gas for proper operation. Physical properties of the sample gas are measured in a fluidic bridge and compared to those of the reference gas whose composition is presumed known. So, the composition of the reference gas must be ensured for the sensor output to be reliable. In aircraft installations, the reference gas is usually drawn from filtered engine bleed air. If the bleed air is heavily contaminated with gaseous contaminants, the output of the sensor will be in error.

Since oxygen is highly paramagnetic, it is possible to calculate the partial pressure of oxygen in the MSOGS product gas by measuring its magnetic susceptibility. Draeger Aerospace have developed a paramagnetic oxygen sensor for use in flight which measures the change in magnetic flux produced by introducing the gas sample in a cyclic manner using a motor drive chopper disc thereby producing an alternating current in pairs of pick up coils. The output of the sensor is markedly affected by temperature and the temperature of the cell is measured continuously so that appropriate corrections can be applied by software. Ambient air is used as the reference gas. The complete sensor includes two measuring cells, chopper motor and electronic unit. It measures oxygen concentration to ± 2 percent.

The most recent solid state oxygen sensor technology is based on ceramic metal oxides, the most common being zirconia (9,13). While normally an electrical insulator, a ceramic zirconium membrane, when doped with traces of metal oxide (typically yttrium oxide) and heated to 600 °C, becomes conductive due to the presence of oxygen vacancies in the crystal lattice. Since conductivity is determined by this specific mechanism, the electrical properties of the material are directly influenced by the surrounding oxygen concentration, which provides the basis for oxygen sensitivity.

While the introduction of solid-state oxygen sensors into aircraft systems offers the possibility of improved performance and reliability, the central role of oxygen monitoring in future OBOG systems places stringent requirements on the sensors that are still not completely satisfied by available technology. There is a pressing need to improve the tolerance of sensors to the hostile environment often encountered in service use. In practice, however, sensor accuracy does not have to be exceedingly high. Tolerance bands of ±5% are acceptable for usable sensors as long as the lower limit of warning tolerance band does not fall below the highest minimum oxygen partial pressure and there is no overlap between the lower control tolerance band and the upper warning tolerance band.

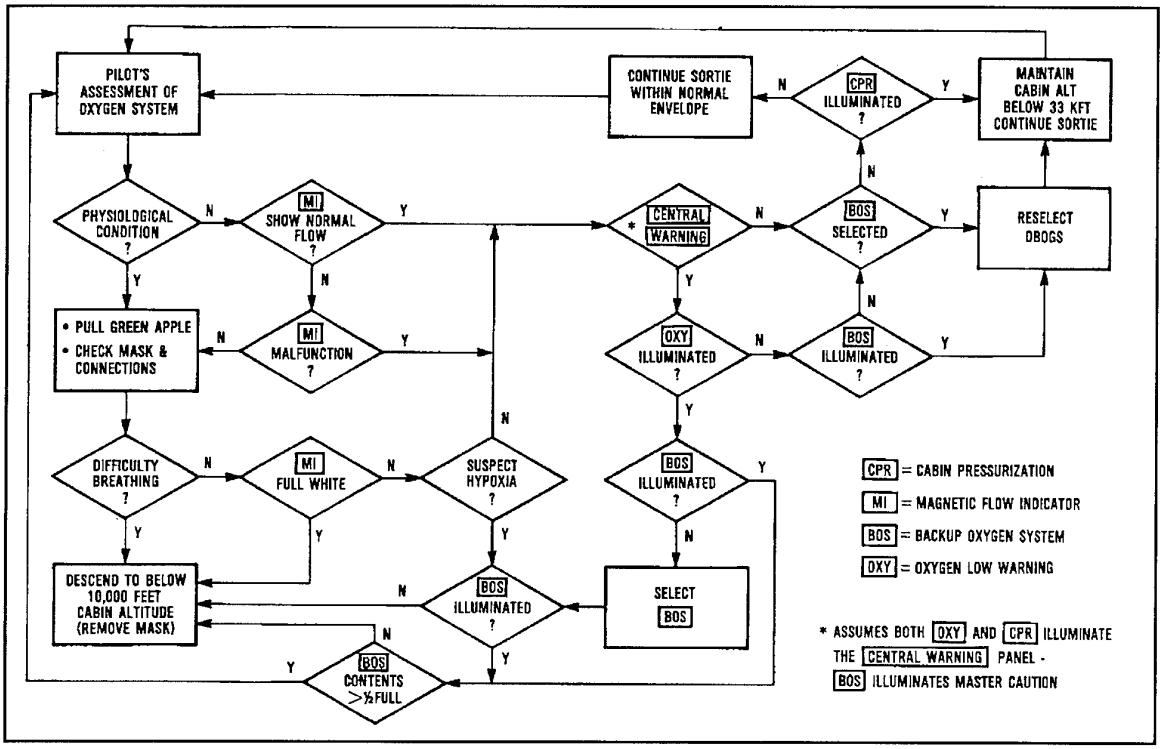

Fig. 10.1 Representative Emergency Action Flow Diagram for an Advanced Oxygen System.

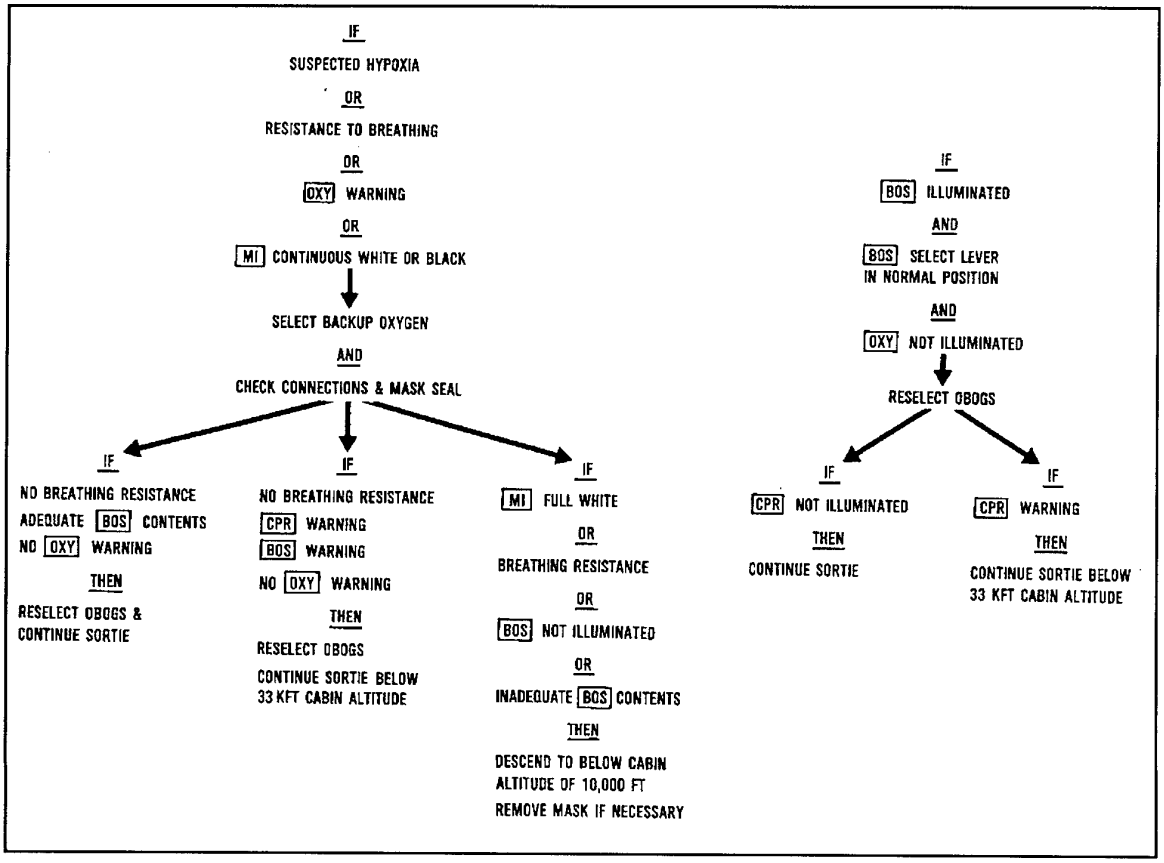

Fig. 10.2 Emergency Action Checklist for an Advanced Oxygen System.

AIRCREW PROCEDURES

As used here the term aircrew procedures will mean the operating instructions given to crews who man AOS equipped aircraft. As noted in Chapter 9, the controls, indicators and warnings in an MSOGS equipped aircraft should correlate, as much as possible, with analogous instrumentation and controls in aircraft equipped with conventional oxygen systems. It is suggested that logic flow diagrams be used to work out crew responses to caution and warning indicators. Such a diagram is shown in Figure 10.1. Any symbology may be used if it is consistent and contains the necessary process, flow, and decision symbols. The process flow chart symbols commonly employed in automated data processing program development are directly adaptable to this use. The primary instrument scan should be represented in the main loop with the various emergency actions represented as decision and process blocks connected in a logical way to lead successful diagnosis of system faults and proper responses. Once the logic of the procedures has been worked out, the crew checklists for the various normal and emergency actions follow naturally. The emergency action checklist in Figure 10.2 is based on the flow diagram from Figure 10.1. It is recommended that procedures be developed with a system fault analysis as suggested in Chapter 9 with the advice and coordination of the prospective aircrew and the aircraft manufacturer.

CONCLUSIONS

New, useful practical information is being gained daily about how to build and the operate airborne MSOG systems advocated for AOS. As with any new technology, MSOGS designers are evolving a body of practical experience as MSOGS finds wider application in a variety of aircraft with varied roles. We are only part way down the MSOGS "learning curve." This chapter contains some of the practical experience likely to be applicable to all AOSs.

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Chapter 11

EFFECTS OF CONTAMINANTS ON MOLECULAR SIEVE OXYGEN GENERATORS

Kenneth G. Ikels

INTRODUCTION

All molecular sieve oxygen generating systems (MSOGS) developed for aircraft use bleed air from a compressor stage of the turbine engine as the source of pressurized feed air. Turbine bleed air is also used for cockpit (cabin) pressurization and air conditioning, and hence is, under normal operating conditions, of good breathing quality. Occasionally, however, the bleed air supply, (including the air supply to the MSOC) can contain contaminants which could adversely affect the performance of the molecular sieve oxygen concentrator and/or be toxic to the aircrew. Contaminants in the ambient air such as occur in the exhaust from other aircraft or, in the event of a chemical attack, from munitions and other ordnance could give rise to toxic chemical compounds which could be ingested by the aircraft engine and pass to the MSOGS. Contaminants could also be generated in situ in the engine or the aircraft environmental control system due to a malfunction of the system or failure of a seal. A seal failure although infrequent, typically results in leakage of lubricating oils or hydraulic fluids, which then undergo pyrolysis and/or decomposition upon exposure to the high temperature of adiabatic compression (14). The volatile and partially oxidized products of pyrolysis can become entrained in the bleed air and contaminate the air supply to the cockpit and MSOGS. This gives rise to the infrequent but nonetheless recurring aircrew complaint of "smoke and fumes in the cockpit." This Chapter considers the effects of possible contaminants in the bleed air supply on the performance of molecular sieve oxygen concentrators.

CONTAMINANTS AND MOLECULAR SIEVES

The extent to which contaminants are adsorbed on molecular sieves depends greatly on the polarity and dipole moment of the contaminant molecule, as well as its size, shape, and degree of unsaturation. The dipole moment is a measure of the center of gravity of negative charge in a molecule, but does not coincide with the center of gravity for the positive charge. This polarity, in turn, provides insight into the structure of the molecule and its ability to be adsorbed by molecular sieves. In general, the greater the dipole moment, the more polar the molecule and the more strongly it will be adsorbed on molecular sieves. Molecular sieves have a very high internal surface area available for adsorption while the external surface of the adsorbent particles contributes only a small amount of the total surface area available for adsorption. The molecular sieves currrently used for separating oxygen from nitrogen have pore diameters of 4.2 Angstrom (type 5A molecular sieve) and 7.4 Angstrom (type 13X molecular sieve, now marketed as OXYSIV-5)(See Chapter 6).

Water

Moisture is a ubiquitous "contaminant" in ambient air. The water molecule is triangular in shape and has an effective diameter of 2.7 Angstrom so that it can easily enter the internal pores of either 5A or 13X molecular sieve. Water has a dipole moment of 1.85 debye (5) which indicates that it is a highly polar molecule. It will therefore be strongly adsorbed by molecular sieves. One of the earlier applications of natural zeolites was the drying of gases and liquids because of the ability of molecular sieves to preferentially adsorb water. Adsorption isotherms indicate that molecular sieves have a high equilibrium capacity for water even when the ambient humidity is low. Further, the isotherms show that a large increase in water loading is accompanied by a relatively small increase in equilibrium vapor pressure until saturation is nearly attained. Even at elevated temperatures, the capacity of the sieves for water remains high. Thus, the dew point of molecular sieve generated aircrew breathing gas is typically in the range from -50 to -20 °C.

While molecular sieve materials adsorb water with relative ease, the performance of molecular sieve oxygen generating systems is relative unaffected by even large amounts of water (6,7). This lack of effect is due to the pressure swing process. During the adsorption or bed loading phase, contaminant molecules including water vapor are retained on the first few centimeters of bed, while oxygen and nitrogen continue to diffuse into and through the sieve particles. During the desorption phase, the sorbed contaminants are stripped from the sieve by the reversed differential pressure and flow. The larger the volume of purge gas, the more effective is desorption of contaminants.

The addition of heat and lowering of the water vapor pressure are required to remove moisture from molecular sieve material and thus cause it to achieve maximum activity (see Chapter 6). This fact appears in direct conflict with the behaviour of pressure swing adsorption systems where contaminants, including water, are easily desorbed by decreasing the bed pressure and reversing the flow. The reason for this apparent discrepancy has to do with the time required for migration of the water molecules from the outer surface of the molecular sieve particle to the internal (cage) microstructure. Once moisture has entered the internal cage of the sieve, the only way to remove water molecules is to raise the temperature (to approximately 350°C) and apply either vacuum or dry gas purge (3). The adsorbed water on the outer surface of the sieve can be readily removed by purge gas at ambient temperature.

The major source of water that may affect the oxygen concentrator is the engine bleed air. Bleed air may contain considerable moisture even though the environmental control system contains a water separator. Rainstorms and engine wash procedures can both lead to ingestion of relatively large amounts of liquid water. Laboratory studies have shown the direct injection of liquid water into the air supply to MSOGS will not affect the composition of the product gas nor cause any long term deactivation of the molecular

sieve itself, provided that the unit is cycling. Thus 600 ml samples of liquid water injected directly into the input of a concentrator had no effect on the product gas (7). Further, there was no deactivation of the molecular sieve. Neither the oxygen concentration nor the dew point of the product gas was affected. It was noted that approximately 60% of the injected liquid was trapped in the coalescence filter, which emphasizes the importance of this component of an MSOG system. Virtually all of the remaining water was purged from the beds during the desorption cycle. Major and rapid deactivation of the molecular sieve material by moisture contamination can be expected when the bed flow is unidirectional for a prolonged period of time; e.g., when the adsorption-desorption cycle is interrupted without cessation of the inlet air flow.

Carbon Dioxide

Carbon dioxide is present in ambient air at a level of approximately 350 parts per million by volume (ppmv). The carbon dioxide molecule has no dipole moment which indicates that the molecule is linear (O=C=O) and has no net charge. It has an equivalent molecular diameter of about 4.6 Angstrom which allows it to enter the pores of molecular sieve type 5A and 13X. However, its lack of polarity dictates that carbon dioxide is not adsorbed to any extent but rather sieved. This characteristic permits a Pressure Swing Adsorption (PSA) system to separate and exhaust carbon dioxide from the air, and indeed, this technique was employed to scrub and remove carbon dioxide from the atmosphere in the U.S. space vehicle Skylab. The concentration of carbon dioxide in the product gas of an aircraft MSOGS supplied with ambient air is less then 1 ppmv. No carbon dioxide appeared in the product gas when the concentration of carbon dioxide in the air supply to a MSOGS was raised to 5000 ppmv.

Carbon Monoxide

Carbon monoxide is a contaminant of concern in the aviation environment. Carbon monoxide has a dipole moment of 0.12 debye (5) and an equivalent molecular diameter of 3.8 Angstrom. Thus carbon monoxide can enter the pore structure of molecular sieve, but it will be only weakly adsorbed due to its low polarity. Although carbon monoxide can appear in the product gas, its concentration is greatly reduced from that in the process air supplied to the MSOGS. In the steady state the reduction of the concentration of carbon monoxide is fourteen-fold for molecular sieve type 5A and nearly twenty-fold for type MG3 sieve (Figure 11.1) (13). Nearly ten minutes is required for the product gas concentration to rise to its equilibrium concentration. Since the threshold limit value for carbon monoxide is 35 ppmv, the presence of carbon monoxide in intake air would not be of concern to MSOG systems until its concentration began to approach 500 ppmv. Modeling studies of airbase environments indicate that the maximum concentration of ambient carbon monoxide from aircraft operations should rarely exceed 10 to 15 ppmv.

Organic Compounds

The extent to which an organic compound adsorbs on or within a particular molecular sieve is determined by the temperature, pressure, polarity, molecular diameter, chemical homogeneity and the degree of unsaturation of the compound. (13). Organic vapor molecules whose kinetic diameter is larger than 7 Angstrom are generally adsorbed on the surface of the crystal lattice during the high pressure feed phase of the pressure swing adsorption cycle, and desorbed during the vent and purge phase, provided the compounds are polar or unsaturated. On the other hand, polar and/or unsaturated organic compounds with a kinetic diameter smaller than 7 Angstrom will be adsorbed on the surface or occluded within the crystal lattice depending on the pore size of the molecular sieve. The latter compounds will also be desorbed during the vent and purge phase of the pressure cycle. Smaller organic molecules, with a kinetic diameter less than 4 Angstrom, and having three or less carbon atoms with no polarity will compete with the oxygen and nitrogen for adsorption sites within the crystal lattice. These compounds will generally find their way through the bed and may appear in the product gas, although at a reduced concentration (7).

Examples of smaller organic molecules that may permeate a molecular sieve bed include methane, ethylene, and acetylene, although it is still true that the more unsaturated the

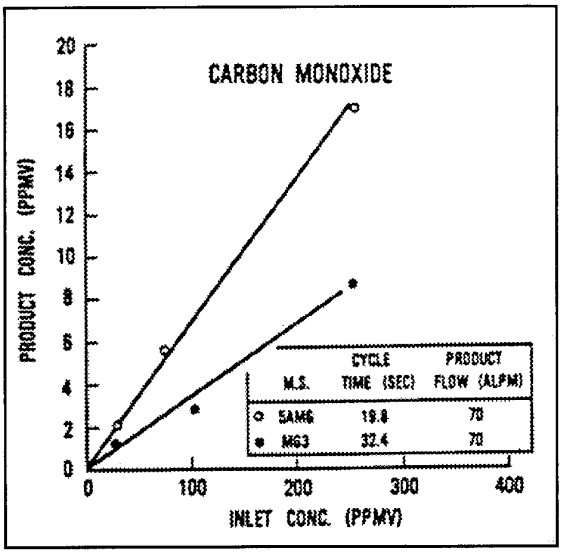

Fig. 11.1 Filtration performance of a molecular sieve oxygen concentrator challenged with carbon monoxide.

molecule, the stronger the adsorptive forces. Since methane, ethylene and acetylene are simple asphyxiants and odorless their presence in product gas does not become significant until their concentrations are sufficient to either cause hypoxia (by materially reducing the oxygen concentration), or become an explosion hazard. Either of these concerns is very remote because of the improbability of prolonged exposure of an aircraft to sufficiently high atmospheric concentrations of these compounds.

Inorganic Compounds

Inorganic gases such as hydrogen chloride, sulfur trioxide, and nitrogen dioxide are strongly adsorbed on molecular sieve, frequently through a chemisorption process which results in the liberation of heat followed by degradation of the sieve due to the formation of strong acids (2). Compounds such as these could have deleterious effects on MSOGS if present in high concentrations for prolonged

periods of time. Such a scenario appears unlikely in an aviation environment. Other acid gases, such as sulfur dioxide, hydrogen sulfide, and chlorine form weak acids and are reversibly adsorbed on molecular sieve without any degradation of the zeolite. The formation of either strong or weak acids with any of these compounds requires the presence of water. Even after several hours of operations, only the first few centimeters of the molecular sieve beds contain adsorbed water, depending on the humidity of the inlet air. Hence, acid formation, if it should occur, will occur at the front ends of the beds.

Ozone is an inorganic gas that may affect MSOGS if the mission profile of the aircraft includes high altitude operations where the atmospheric concentration of ozone can reach concentrations as high as 16 ppmv (12,15). Ozone has a kinetic diameter of approximately 4 Angstrom and a dipole moment of 0.53 debye. These physical characteristics indicate that ozone should be reversibly adsorbed on molecular sieve, in the first few centimeters of the bed, and be eliminated during the purge cycle. Ozone is unlikely therefore to appear in the product gas. This conclusion was confirmed in an experimental study in which a three-bed MSOGS filled successively with 5AMG and MG3 molecular sieve was supplied with air containing up to 10 ppmv of ozone while operating at a simulated aircraft altitude of 40,000 feet (12). The concentration of ozone in the product gas was approximately one thousandth of the inlet concentration with both types of molecular sieve. This study emphasized that the components of an MSOGS which may be exposed to high concentrations of ozone should be constructed of ozone resistant materials.

CHEMICAL WARFARE AGENTS

The spectre of chemical warfare has raised the obvious concern that (CW) agents might be present in the product gas of an MSOGS when an aircraft is operating in an CW environment or might impair the oxygen concentrating performance of the molecular sieve. A joint US-UK program was established to investigate these questions in the early 1980s. The Small Molecular Sieve Oxygen Concentrator described in Chapter 6 was developed as part of this program in order to provide a facility to study the effects of both live CW agents and CW agent simulants upon MSOGS and to provide a guide as to the conditions which should be used in the full scale testing of the effects of live CW agents on aircraft MSOGS concentrators.

Chemical Warfare Agent Simulants

Dimethyl methyl phosphonate (DMMP) was the primary CW agent simulant employed in studies of the behavior of MSOGS. DMMP has a boiling point and viscosity which are quite similar to Soman (GD). Simulant trials conducted at the Chemical Defence Establishment, Porton Down, UK using a Small MSOC showed that even large doses of DMMP in the air supply to the concentrator had no effect on the efficiency of oxygen-nitrogen separation, nor was any DMMP observed in the product gas (4). When the concentrator was packed with type 5A molecular sieve, mass balance on the process air indicated that nearly 87% of the DMMP was purged from the bed during the backflush cycle. When the concentrator was packed with type 13X molecular sieve, only about 37% of DMMP was purged from the bed, which indicated a much greater retention of DMMP by the molecular sieve with the larger pore size.

The use of DMMP and different molecular sieves in the Small MSOC provided an opportunity to explore how sieves react toward specific compounds. Although DMMP and Soman (GD) have similar boiling points and viscosities, Soman is considerably more polar than DMMP owing to the presence of a fluorine atom. It would be expected therefore that Soman would be more strongly adsorbed to molecular sieve than DMMP and that a higher fraction of Soman would be irreversibly adsorbed. Molecular sieves have an extremely high capacity for Soman and it is unlikely therefore that GD would appear in the product gas (4).

Chemical Warfare Agents

There have been several studies of the effects of live CW agents on molecular sieves and aircraft molecular sieve oxygen concentrators (1, 8,9,10). The major study in the joint US-UK program was conducted at the US Army Dugway Proving Ground, Utah between 1983 and 1985 (1). The tests were conducted on a Litton two man MSOC designed for the F16 aircraft (See Chapter 8). The protocol was designed to determine the effects of conventional CW agents upon the oxygen concentrating performance of the MSOC, to determine whether CW agent appeared in the product gas and to determine the proportion of the CW challenge which appeared in the exhaust gas. Special support facilities were developed at Dugway to enable safe studies to be conducted using hydrogen cyanide (AC), Sarin (GB), Soman (GD) and distilled mustard (HD). The MSOC under test was supplied with air at 43 lbf in^{-2} g (396 kPag) and a continuous product gas flow of 60-100 L (ATPD) min^{-1} was demanded from the concentrator. Trials were conducted at various temperatures of the inlet air (25-75 °C) and with humidities varying between 10 and 80%. Challenges comprising single CW agents were made by establishing specified concentrations of the agent in the inlet air to the MSOC for a specified period of time between 5 and 50 minutes to give the required Challenge Dosage which was expressed as the product of concentration of the agent (mg m^{-3}) and the time for which it was present (min) - the Ct (mg.min.m^{-3}). The CW agent challenges employed are summarized in Table 11.1. The studies showed that under the conditions investigated, conventional CW agents (AC, GB, GD and HD) had no significant impact on the performance of the MSOC, or on the concentration of oxygen in the product gas. It was further confirmed that no CW agent appeared in the product gas. A parallel study conducted at the Canadian Defence Research Establishment at Suffield, Alberta reached a similar conclusion (10).

Table 11.1 The CW challenges used in the Dugway Proving Ground tests of a molecular sieve oxygen concentrator (1).

Agent	Average Trial Challenge Dosage C.t mg.min m-3	Total Challenge C.t mg.min m-3	Number of Trials
Hydrogen Cyanide (AC)	18,000	199,130	24
Sarin (GB)	1,500	38,196	32
Soman (GD)	200	4,208	25
Distilled Mustard (HD)	600	9,792	15

In concert with the chemical warfare agent challenging of MSOGS, considerable work has also been conducted in the area of PSA systems (9,16) designed to produce contaminant free air under chemical warfare conditions. PSA systems designed for producing contaminant free product gas generally utilize type 13X molecular sieve. An extensive study of a small scale PSA system built by the Pall Corporation was conducted by the TNO Prins Maurits Laboratory (9). The challenges included four live agents, two simulants, and a toxic volatile compound performed repeatedly over a period of six months. The system consistently met stringent effluent purity criteria for each of the challenge vapors.

It may be concluded from these studies that conventional chemical warfare agents are extremely unlikely to affect the oxygen concentrating performance of present designs of MSOCs. These units are also effective in continuing to deliver product gas free of CW agents when realistic challenges of CW agents are present in the air supply to a concentrator. A valuable summary and review of the work performed in this area between 1979 and 1992 has been written by Jones et al (8). It is doubtful however, whether an MSOC should ever be employed as the sole means of removing chemical agents from the product gas delivered to the air crew member. Other considerations generally require that the gas delivery system to an aircrew NBC respirator includes a body mounted NBC filter.

In addition to the chemical agent challenges, Dugway Proving Ground also conducted a series of biological warfare agent tests of the coalescent particular filter used in the MSOC (17). The tests were designed to determine the effectiveness of the filters in removing biological agents from contaminated inlet air. The biological simulants used were bacterial spores of Bacillus Subtilis var, niger (BG), and a vegative bacteria Serratia Marcescens strain UK8 (SM). The average filter efficiency was 99.996 percent under the conditions tested.

QUANTITATIVE ASSESSMENT OF MOLECULAR SIEVE ACTIVITY

The condition of the air supply to an MSOGS in an aircraft may be such that slow degradation of the molecular sieve in the oxygen concentrator occurs over time due to long term exposure to moisture or other contaminants. It is valuable therefore, to be able to assess the residual activity of a molecular sieve bed. Two relatively simple procedures have been developed for this purpose.

One (6) test first saturates the bed of molecular sieve with oxygen, and then measures the time taken to replace the oxygen with nitrogen. The gases are then reversed and the time taken to replace nitrogen with oxygen is determined. Similar measurements of replacement times are made under the same conditions of flow rate, temperature and bed geometry using fresh (fully activated) molecular sieve. If the time taken to replace the oxygen from the bed under test is less than half that obtained with fully active molecular sieve then the bed under test must be considered to be only marginally effective, and the molecular sieve should be replaced with fresh material.

Another test (11) measures the activity or adsorption capacity of the molecular sieve bed. The activity is defined as the ratio of the weight of nitrogen adsorbed in the bed under test, to the weight of nitrogen adsorbed by an identical bed containing fully activated molecular sieve (of the same type). The activity of the test bed is expressed as a percentage of the maximum. As molecular sieve activity decreases, the nitrogen adsorption capacity diminishes. In this test, the bed is first filled with helium to determine the bed void volume. The bed is then pressurized with nitrogen to about 60 lbf in^{-2} g (414 kPag) and the weight change is recorded. By using measured values of pressure, temperature, and weight, the true weight gain due to nitrogen adsorption can be calculated. This value is then compared with the known nitrogen adsorption capacity of fully activited molecular sieve.

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14. Abstract

Many of the oxygen systems fitted to present NATO aircraft are unsatisfactory as they employ liquid oxygen which requires a complex and expensive supply chain, they impose undesirable physiological loads on the aircrew, particularly high resistance to breathing, and they do not provide pressure breathing with +Gz or effective protection to the respiratory tract and eyes against NBC agents. Advanced Oxygen Systems (AOS), which provide on board generation of breathing gas, impose a low physiological load on the aircrew and provide pressure breathing with G and at high altitude and protection against NBC agents, are required in the new generation of very agile high performance combat aircraft now under development by the NATO nations.

This monograph provides a comprehensive review of the present state of development of AOS for combat aircraft and provides practical guidelines for the future development of these systems.

The monograph comprises an Introduction (Chapter 1); conventional US and UK Oxygen systems and their deficiencies (Chapter 2); the history of development of on-board oxygen generating systems, OBOGS (Chapter 3); operational requirements and design of AOS (Chapter 4); physiological requirements for AOS (Chapter 5); molecular sieves, pressure swing adsorption and oxygen concentrators (Chapter 6); breathing gas regulators and masks for AOS (Chapter 7); current molecular sieve oxygen generation systems (Chapter 8); sensors, indicators and controls for AOS (Chapter 9); practical aspects of design of AOS (Chapter 10); and effects of contaminants, including chemical warfare agents, on molecular sieve oxygen generators; and an Index.

This monograph will be of value to all those concerned with the design, procurement and operational use of Advanced Oxygen Systems to be fitted to future high performance combat aircraft.

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